Development of

HIGH-TEMPERATURE, HIGH-CURRENT, ALKALI-METAL, VAPOR-FILLED CERAMIC THYRATRONS AND RECTIFIERS

by

A. W. Coolidge

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-6005

GENERAL ELECTRIC

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FINAL REPORT

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HIGH-TEMPERATURE, HIGH-CURRENT, ALKALI-METAL VAPOR-FILLED, CERAMIC THYRATRONS AND RECTIFIERS

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February 15, 1966

CONTRACT NAS3-6005

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Cleveland, Ohio
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A revised text of this report is being prepared for publication as a low number NASA contractor report.

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FOREWORD

The report has been prepared by the Microwave Tube Business Section, General Electric Company, under National Aeronautics and Space Administration Contract NAS3-6005.

This work was administered under the direction of Mr. E. A. Koutnik of the Space Power Systems Division, Lewis Research Center, Cleveland, Ohio.

This report covers the work performed from 19 June 1964 to 19 October 1966 by the General Electric Tube Department, Microwave Tube Business Section.

Development of

HIGH-TEMPERATURE, HIGH-CURRENT, ALKALI-METAL VAPOR-FILLED CERAMIC THYRATRONS AND RECTIFIERS

by A. W. Coolidge
General Electric Company

SUMMARY

The purpose of National Aeronautics and Space Administration Contract NAS3-6005 was to advance the technology and to provide fundamental design data for high-temperature, high-current, alkali-metal, vapor-type ceramic tubes. The objectives of this program were to conduct a fundamental investigation of the problem areas associated with high-temperature, vapor-type tubes, and to fabricate and test prototype rectifiers and thyratrons to prove the technology and to provide application data for future reference.

Alkali halides were evaluated as vapor-fill materials for tubes working with a heat-rejection temperature of 600°C. Using cesium iodide, there was insufficient dissociation of the alkli halide to permit the tubes to operate in the manner of cesium-filled tubes. Also, there appeared to be a reaction between the halide and one of the materials in the ceramic-to-metal seal.

The use of alkali halide was discontinued in favor of free cesium.

The emission properties of cesium are so high that it became necessary to restrict the temperature of a molybdenum anode to 400°C in order to avoid inverse anode current. Zirconium carbide and hafnium, which have more suitable work functions, were tried as anode materials but judged to be essentially the same as molybdenum.

To counter anode and grid emission, four additional fill materials were considered. None would permit the formation of a highly emitting film, such as that associated with cesium to the end that a substantial increase in the operating temperature of an anode and grid could be realized. However, a prepared cathode, such as a barium system or a thoriated-tungsten system, would be required.

One of the materials, thallium, was tested in a diode for 500 hours and appeared promising as a vapor-fill material in a tube required to work into a 600°C heat sink.

When a study indicated that the over-all efficiency of cesium-filled tubes would surpass that of tubes filled with other eligible materials, the customer redirected the contract to permit the use of cesium with a heat-rejection temperature in the 300°C range.

Three 15-ampere cesium-filled thyratrons were built and tested. One tube was subjected to an endurance run.

INTRODUCTION

This final report on Contract NAS3-6005 covers the period 19 June 1964 to 19 October 1966. The purpose of this contract was to advance the technology and to provide fundamental design data for high-temperature, high-current, alkali-metal, vapor-type ceramic tubes. The objectives of this program were to conduct a fundamental investigation of problem areas associated with high-temperature, vapor-type tubes, and to fabricate and test prototype rectifiers and thyratrons to prove the technology and to provide application data for future reference.

The original program was divided into two major parts.

PHASE I

Phase I of the program was concerned with the investigation of fundamental problems and the establishment of the conceptual design of prototype models that would meet the objective ratings. Specific tasks were:

1. The selection of the alkali-metal vapor which would produce the lowest voltage drop and reduce temperature dependence.

2. A study of the compatibility problems to determine the materials to be used with the selected alkali-metal vapor.

3. A study of ceramic-to-metal seal techniques to determine the materials and the types of seals.

4. A study of tube-element design and geometry to determine the best combination for minimum size and weight, and for maximum reliability.

5. An investigation of mounting methods to determine which are best suited for resisting mechnical shock and for removing heat from the elements.

6. Development of a tube having the following ratings:

    (a) forward voltage, 300 volts
    (b) inverse voltage, 750 volts
    (c) average current, 15 amperes
    (d) frequency range, 400-2000 cycles per second

PHASE II

Phase II of this program was concerned with the final design fabrication, and testing of tubes, based on conceptual designs produced in Phase I and having ratings as follows:

(a) forward voltage, 200 volts
(b) inverse voltage, 750 volts
(c) average current, 150 amperes
(d) frequency range, 400-2000 cycles per second

CONTRACT REDIRECTION

In August 1965 the technical effort for the balance of the contract was redirected.

Phase II tubes were excluded, and effort was concentrated on the design, fabrication and testing of three 15-ampere cesium-filled thyratrons.

TECHNICAL DISCUSSION AND PROGRESS

GENERAL

Vapor-filled and gas-filled control tubes have been widely used in industrial and military applications. Both types exhibit a low arc drop and, consequently, a low loss. Compared to gas-filled tubes, the vapor type exhibits the advantage of being free from gas clean-up, but contains the restriction of a relatively narrow operating-temperature range since the vapor pressure is a function of the temperature of the vapor condensate.

The most common type of vapor-filled control tube is the mercury thyratron. At room temperature, or at relatively low ambient temperatures, the vapor pressure of mercury is appropriate for thyratron operation (Figure 1).

Cesium has been employed to a lesser extent as the ionizing agent in control tubes. However, because of the relatively lower vapor pressure of cesium (Figure 2), it has been necessary to use these tubes with external heaters, or at elevated ambient temperatures, to maintain the cesium temperature between 150 and 250°C.

More recently, cesium has been used as the ionizing agent in vapor thermionic converters, where optimum operating characteristics are realized when the cesium vapor pressure is about 1.5 millimeters of mercury with a corresponding cesium reservoir temperature of 300°C. In the thermionic converter, the presence of cesium greatly enhances cathode emission by means of a process where a monolayer of cesium is deposited on the cathode substrate surface, causing a substantial reduction in cathode work function. Cesiated cathode emission densities of 10 to 20 amperes per square centimeter have been readily obtained in the thermionic converter.

For a vapor-filled thyratron to operate in the 600°C range, a material must be selected with a vapor pressure of 50 to 500 microns at that temperature. In addition, proper attention must be given to the design of the seals and to the problem of suppressing unwanted anode or grid emission.

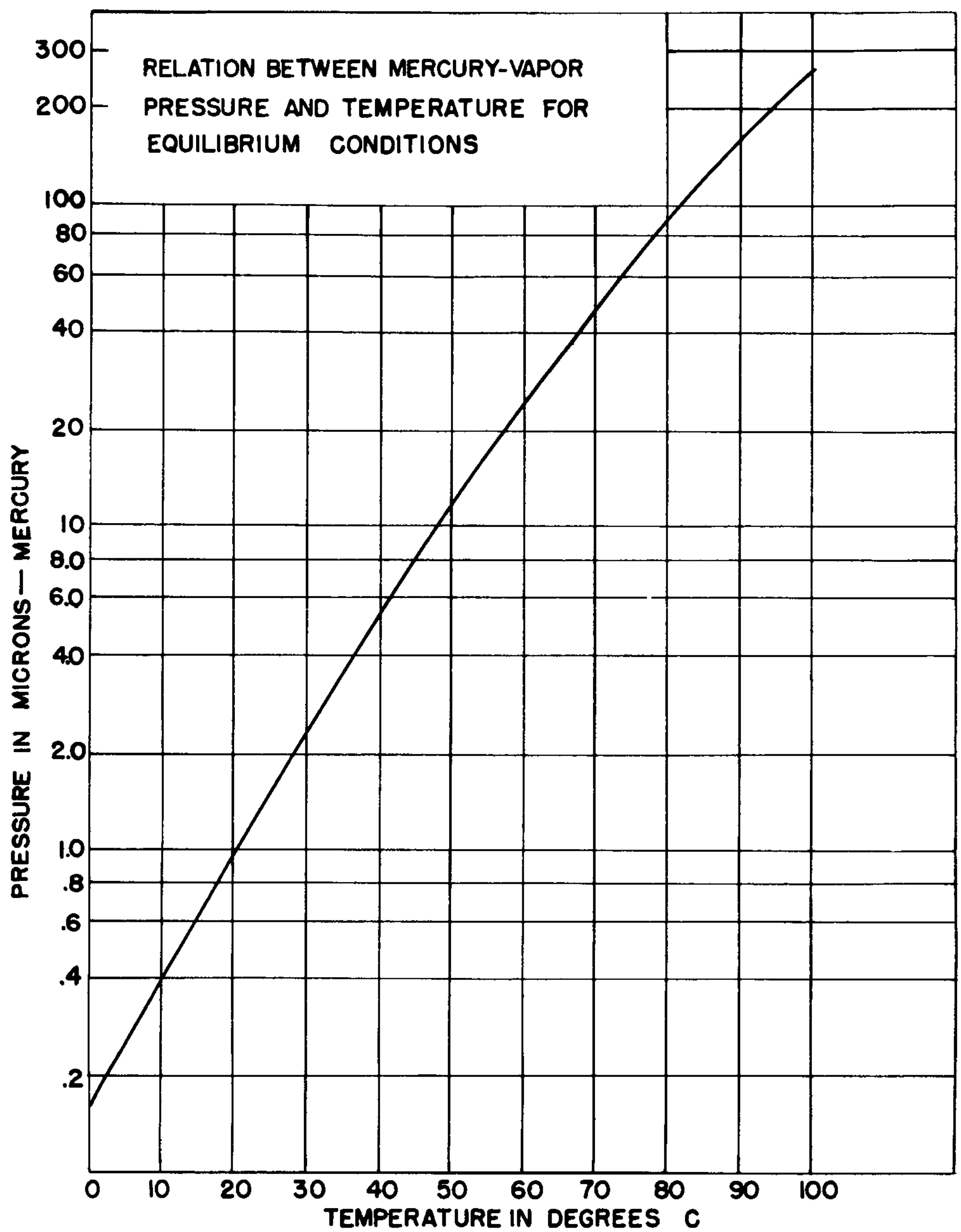

Figure 1 - Relation between Mercury-Vapor Pressure and Temperature for Equilibrium Conditions

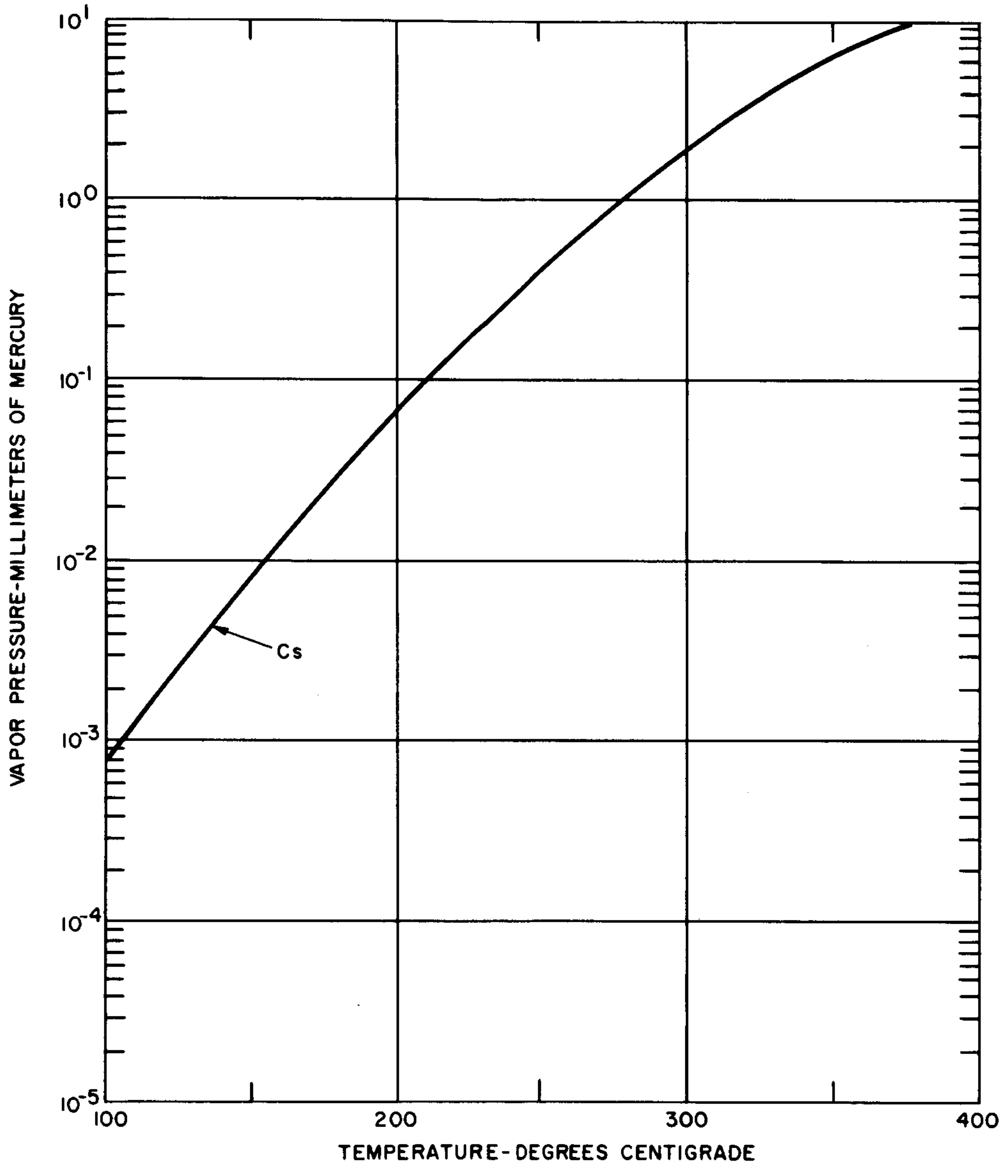

Figure 2 - Relation between Cesium-Vapor Pressure and Temperature for Equilibrium Conditions

At $600^{\circ}C$, the equilibrium vapor pressures of mercury and cesium are several thousand and several hundred millimeters, respectively. Unquestionably this is excessive. However, four elements and four halides of cesium have interesting vapor pressures at this elevated temperature. They are:

1. Thallium
2. Lead
3. Bismuth
4. Antimony
5. Cesium iodide
6. Cesium fluoride
7. Cesium bromide
8. Cesium chloride

Vapor pressure data for the above is presented in Figures 3 and 4.

To preclude arc-backs or loss of grid control, the work function of the anode and grid should be high enough to limit the emission to a maximum of 10^{-6} amperes per square centimeter. This necessitates a work function of at least three electron volts at a temperature of 1150 degrees Kelvin.

ALKALI HALIDE DIODES

One of the tasks was to determine whether an alkali-halide-filled tube might function as a cesium tube as a result of dissociation of the compound at $600^{\circ}C$.

A major consideration for envelope design is compatibility. Considerable background was available regarding compatibility of envelope materials with cesium, but there was little information regarding their resistance to halogens. Since it was hoped that the tube under consideration would function as a cesium tube, it was considered necessary to select materials known to have good resistance to attack from cesium. These included the refractory metals and high-alumina-content ceramics, such as lucalox.*

For the initial test vehicle, a simple diode structure, similar to an existing thermionic vapor converter, was selected. This structure, shown

*General Electric Trademark for high-purity alumina body.

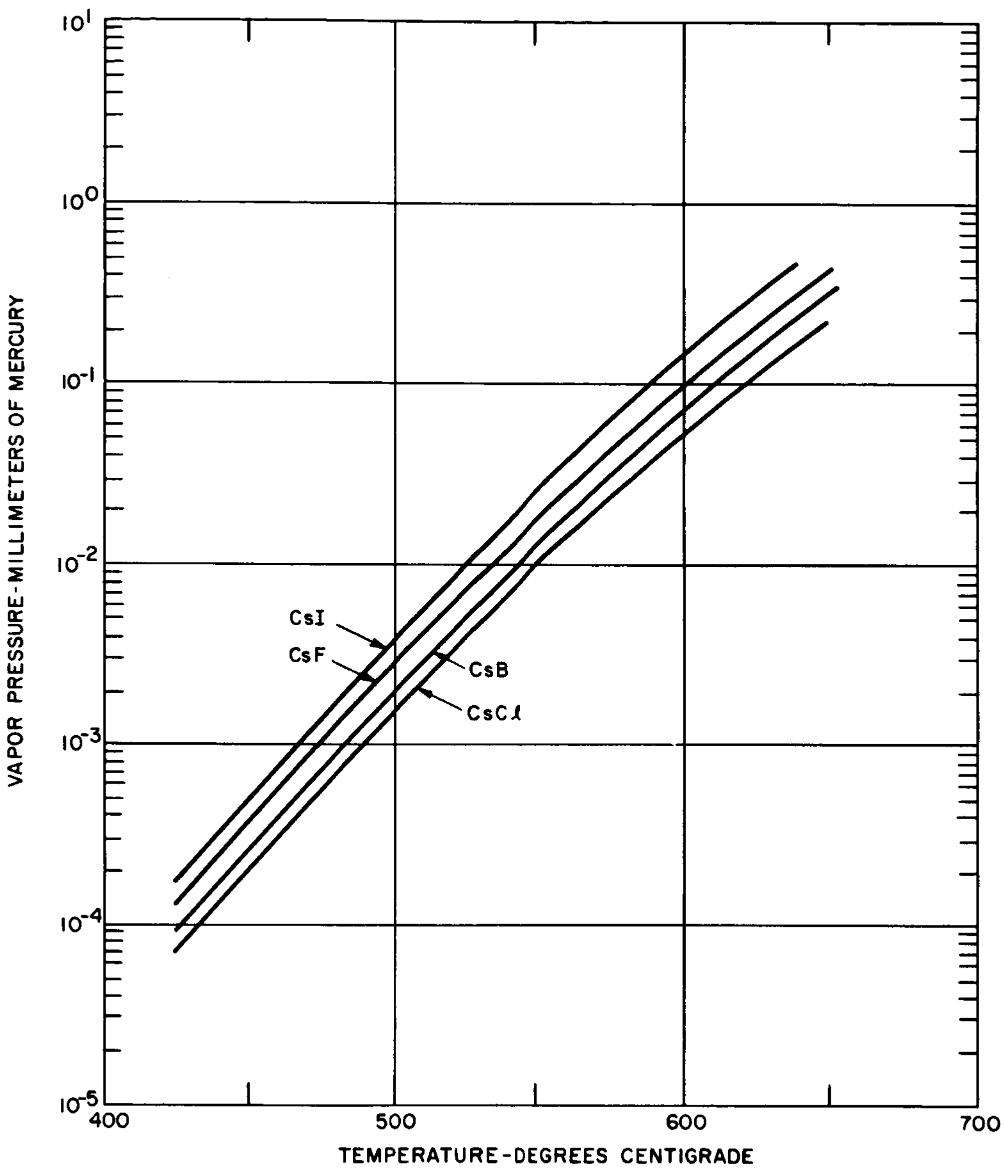

Figure 3 - Relation between Alkalide-Halide-Vapor Pressure and Temperature for Equilibrium Conditions

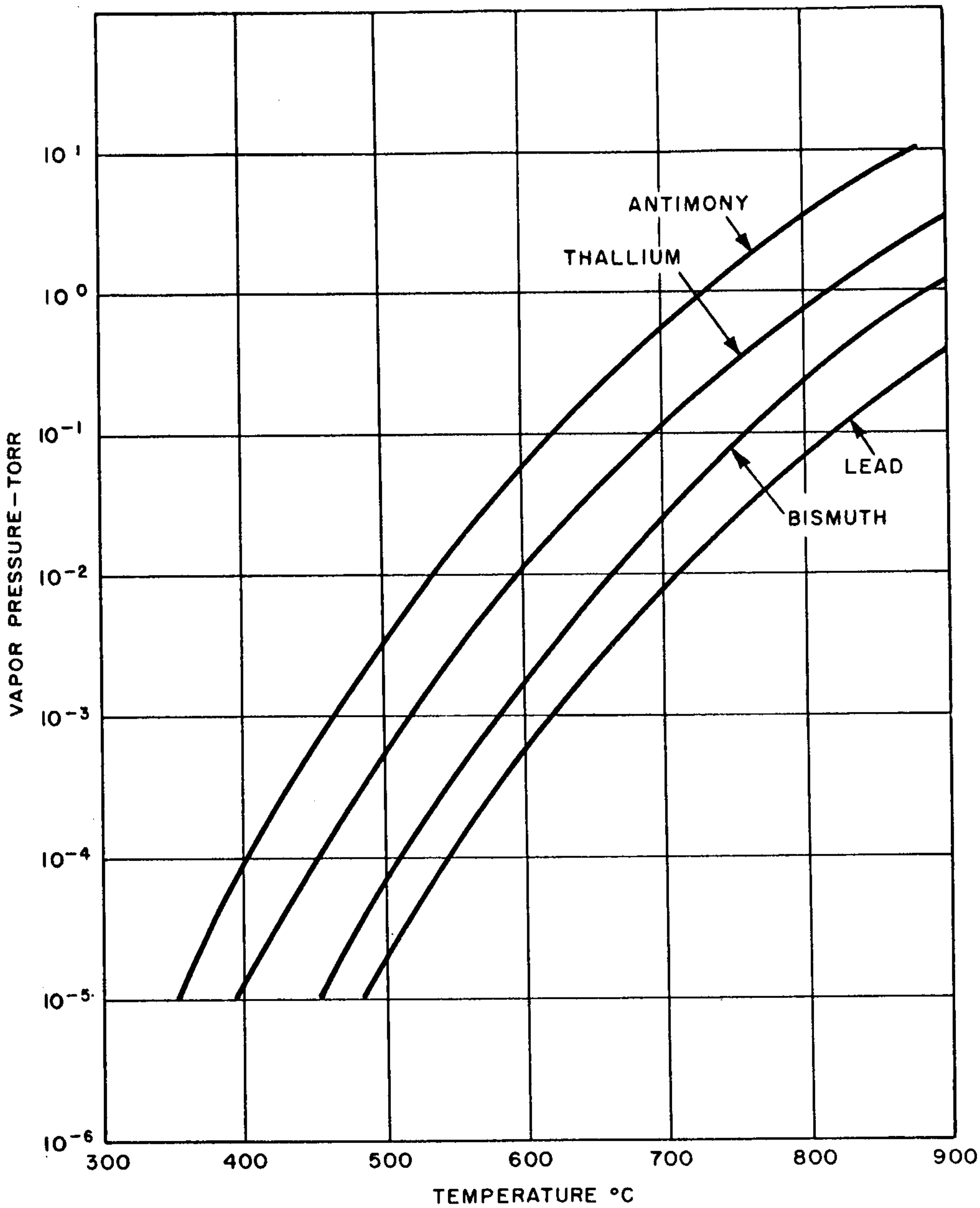

Figure 4 - Relation between Antimony, Thallium, Lead and Bismuth Vapor Pressures and Temperature for Equilibrium Conditions

in Figure 5, consists of a molybdenum emitter, heated by an external oven, and a closely spaced molybdenum anode. Attached to this is a tantalum tubulation containing a pellet or reservoir of alkali halide, the temperature of which is controlled by a second oven. The main body of the tube, which is about as large as a one-inch cube, is placed inside a third oven. By means of independent oven-temperature control, it was possible to operate the main structure in an ambient temperature to 800°C and increase the emitter temperature to 1400°C. Because of its remote location, the reservoir temperature could be operated from about 200 to 600°C.

The first tubes, Type Z-7009, Tube Nos. 1 and 4, were made with cesium iodide being selected as the alkali-halide fill.

As the tubes were studied on test, it was apparent that the conduction characteristics in forward and inverse directions were essentially the same. Further, the tubes looked like low-impedance resistors at elevated temperatures and high-impedance (about 20 megohms) resistors at room temperature.

When one tube was opened, a generous metallic coating was evident on the ceramic separating the anode and cathode flanges. X-ray spectroscopic analysis of the coating identified titanium, nickel, cesium and iodine. A titanium-halogen cycle was suspected as the cause of the coating.

A titanium-halogen cycle permits free titanium to combine with free iodine, with the titanium-iodide product migrating throughout the interior of the tube. Subsequent partial dissociation of the salt occurs leaving free titanium (displaced from its original location) and free iodine. Such a cycle repeats until the relocation of free titanium, associated with localized temperature differences within the tube, produces equilibrium.

The first tubes employed tantalum flange seals, high-purity alumina ceramic, and nickel-titanium brazing washers containing a surplus of titanium so that the resulting eutectic melted at 942°C, Figure 6. Possible ways to counter the halide cycle were as follows:

1. Variation of titanium-nickel ratio
2. Nickel plating the titanium bearing seal area
3. Selection of a sealing material which is not subject to halogen reaction.

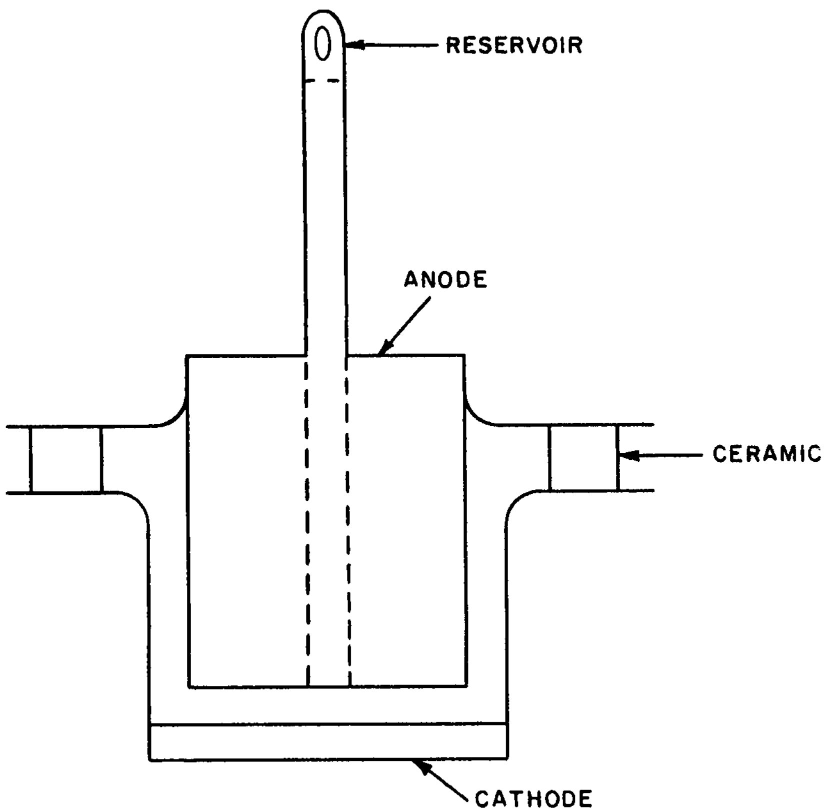

Figure 5 - Schematic of Initial Test Vehicle, Design A

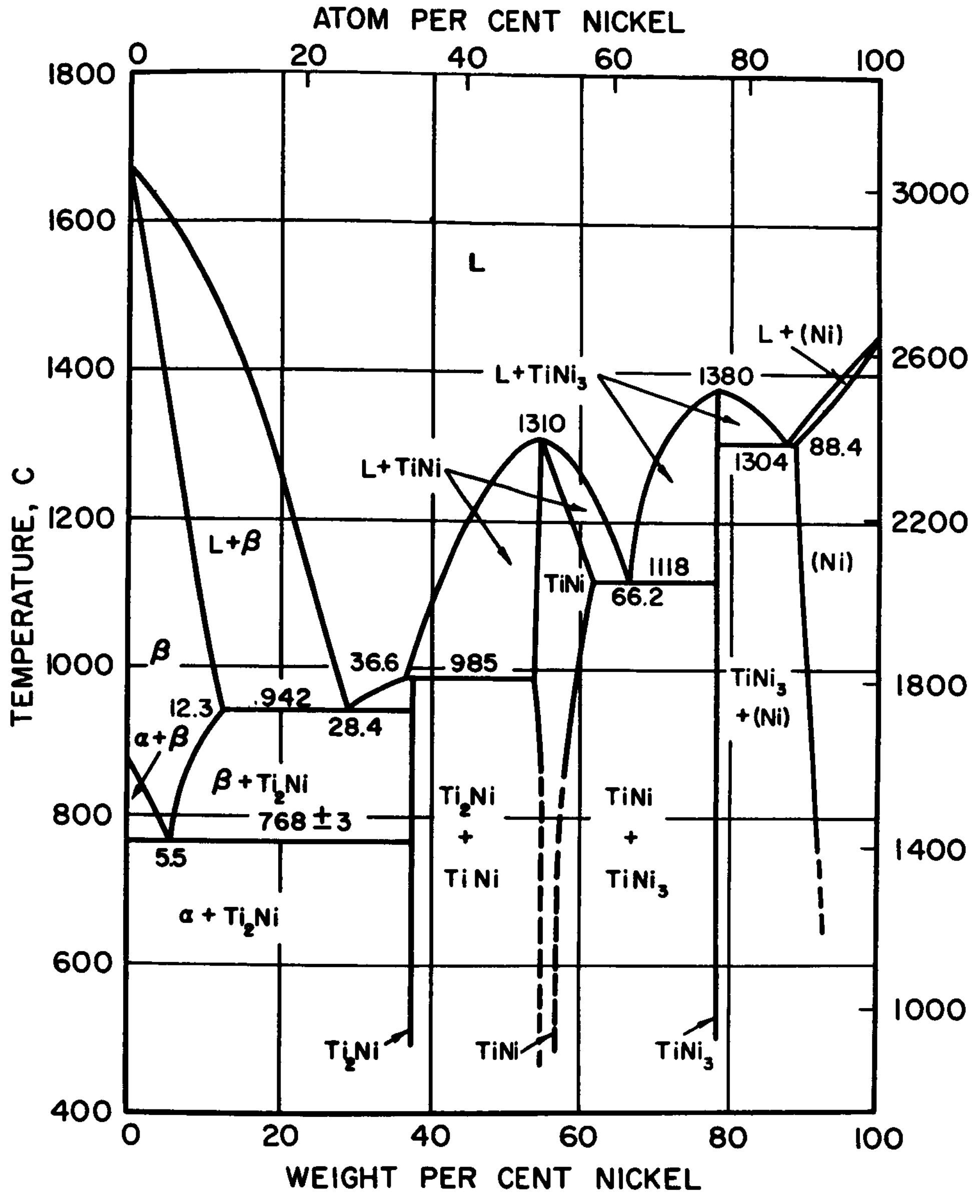

Figure 6 - Nickel-Titanium Phase Diagram

By increasing the ratio of nickel to titanium, the resulting seal could be effected at 1280°C, with the resulting braze consisting primarily of $Ti\ Ni_3$ plus Ti Ni, as shown near the right-hand side of Figure 6. More important, however, is the fact that there would be less free titanium at the seal structure to trigger a titanium-halogen cycle.

Several attempts to fabricate seals with the $Ti\ Ni_3$ were unsuccessful; it was concluded that the material was more brittle than the $Ti_2\ Ni$ alloy and thus unsuitable for further study.

Type Z-7009, Tube No. 6, was fabricated with nickel-titanium brazed seals, with the seal area covered by a layer of nickel plating. This approach proved to be inadequate in protecting against formation of a halogen cycle. Although the cold impedance of the tube was initially 18,000 ohms, the impedance fell precipitously during test to a fraction of an ohm.

Tube No. 5 utilized a sealing alloy of palladium and cobalt, known as "Palco." Since this alloy does not wet tantalum, molybdenum flanges were sealed to the ceramic.

The inter-electrode resistance of the tube, when cold, was greater than 20 megohms and fell to a minimum of 1,000 ohms when hot (reservoir = 650°C, cathode temperature = 1100°C). Such a leakage path could be formed by cesium, or the apparent tube impedance could have been caused by emission from the anode and cathode. In any event, the hot (1,000 ohm) resistance was high enough to permit the tube to be studied as a rectifier. After a number of heat cycles, the cold impedance fell to 1.3 megohms. While this is a significant reduction from the original impedance, the impedance is several orders of magnitude higher than that of comparable tubes made with nickel-titanium brazing alloy.

Some cathode emission was observed, although only with a high tube drop of about 50 volts at 5 amperes peak. Thus, either inadequate dissociation of the cesium iodide was occurring, or the presence of negative ions was adversely affecting tube losses.

Two suggestions were made for enhancing the prospect of attaining lower tube drops with a cesium-iodide fill. Both were intended to increase the amount of free cesium in the tube.

1. Inserting an additional hot electrode or hot wire in the tube which would also produce surface ionization

2. Seeding the tube with a certain amount of free cesium when the tube is processed and exhausted

It was apparent that an outstanding degree of success had not been realized in the early alkali-halide filled tubes. Although there had not been enough investigation to conclude that alkali-halide tubes were not practical, it became obvious that considerable additional work would be required in any event, and tube design and operation were to become more complex.

Consequently, at this point the customer directed that pure cesium-filled tubes be studied. The heat rejection requirements were relaxed to permit the cesium reservoir to operate with a heat sink in the 300°C range, with the rest of the tube coupled to a 600°C heat sink.

CESIUM-FILLED DIODES

The early cesium-filled diodes utilized a thermionic converter structure, Figure 5, with a molybdenum cathode and anode.

Type Z-7009, Tube Nos. 2 and 3, were identical except that Tube No. 2 had an anode-to-cathode spacing of 0.030 inch, while in Tube No. 3 the spacing was 0.010 inch.

When these tubes were operated at currents up to 15 amperes on the average, extremely low arc drops were observed. Indeed, at low average currents and high cathode temperature, the tube drop was actually negative, indicating that the tube was capable of "generating" in a manner similar to that of a thermionic converter. Emission data is summarized in Figures 7, 8, 9, and 10. As can be seen from these illustrations, the closest spaced tube exhibited the lowest drop. Under pulse conditions, the tube was loaded with a current of 104 amperes, equivalent to about 20 amperes per square centimeter, with a tube drop of 1.6 volts. The tube drop for a thyratron would necessarily be higher because of losses at the grid and increased plasma losses attending the longer path between cathode and anode.

The ability of a thyratron to hold off high anode voltage depends upon the suppression of grid emission to a low value. Moreover, if the tube is to withstand high inverse voltages, reverse current caused by emission from the anode must be negligible. Cold breakdown will occur when the voltage exceeds the "PD" or Paschen limitation regardless of the electrode temperatures.

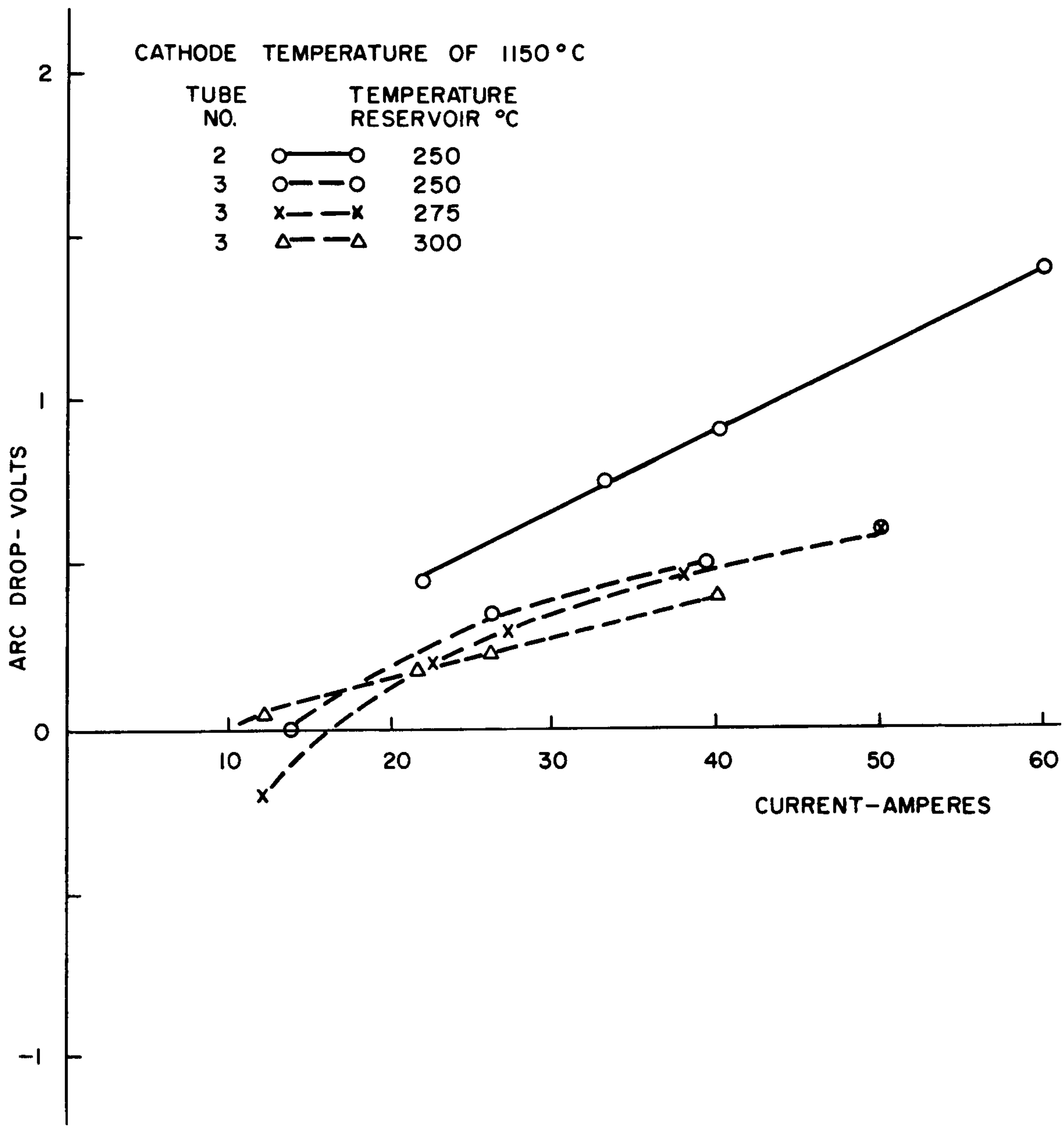

Figure 7 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1150°C

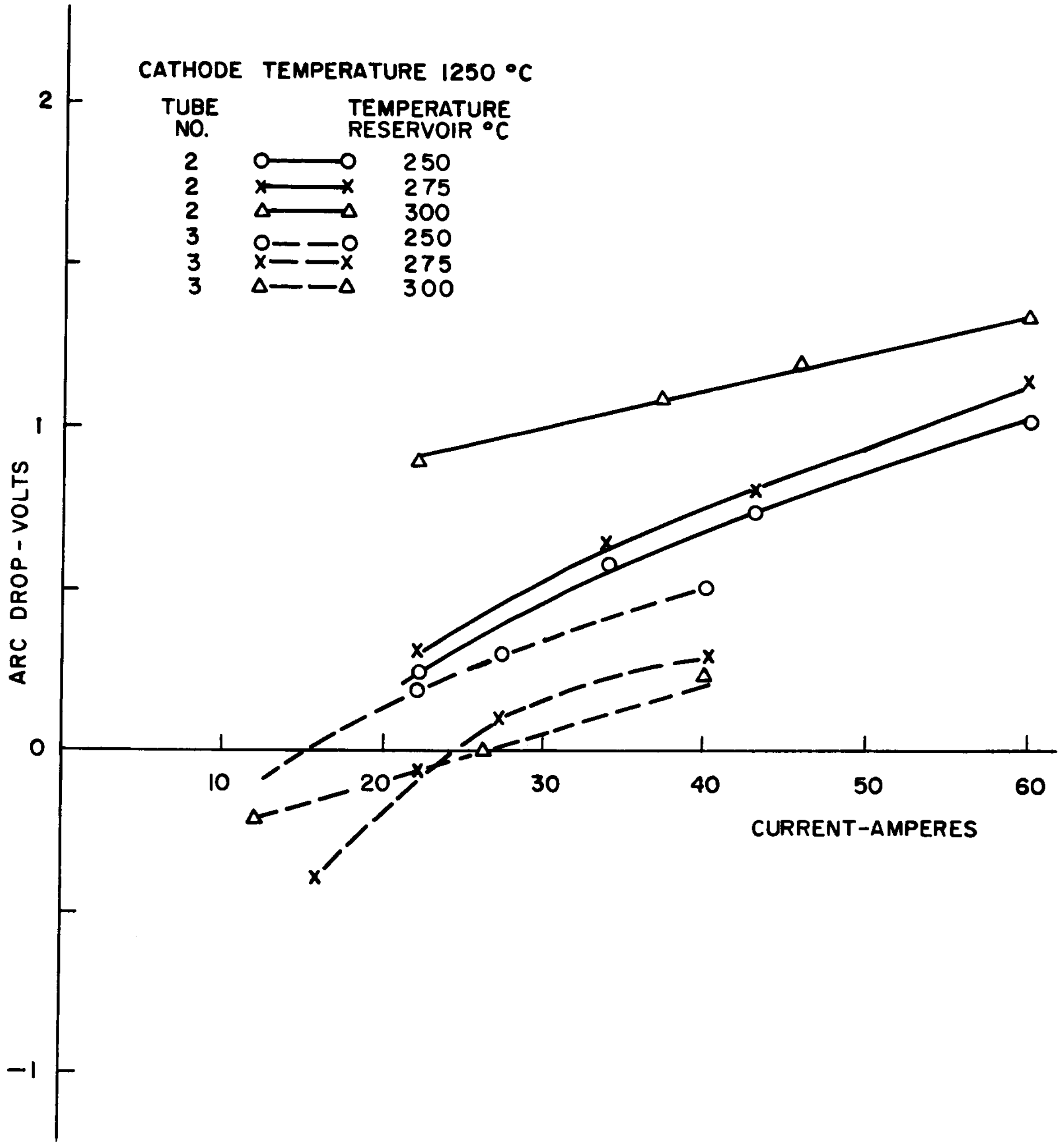

Figure 8 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1250°C

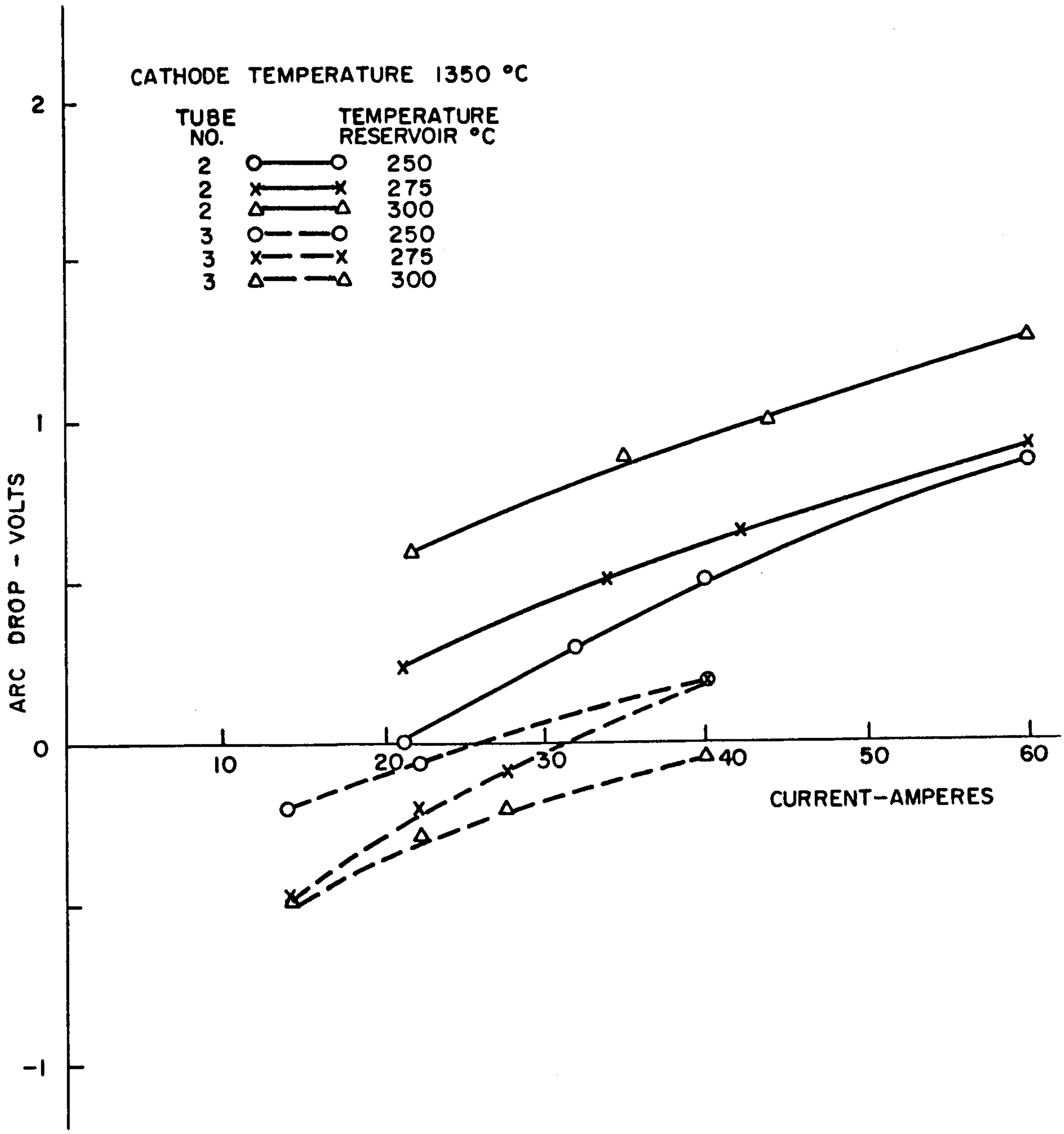

Figure 9 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1350°C

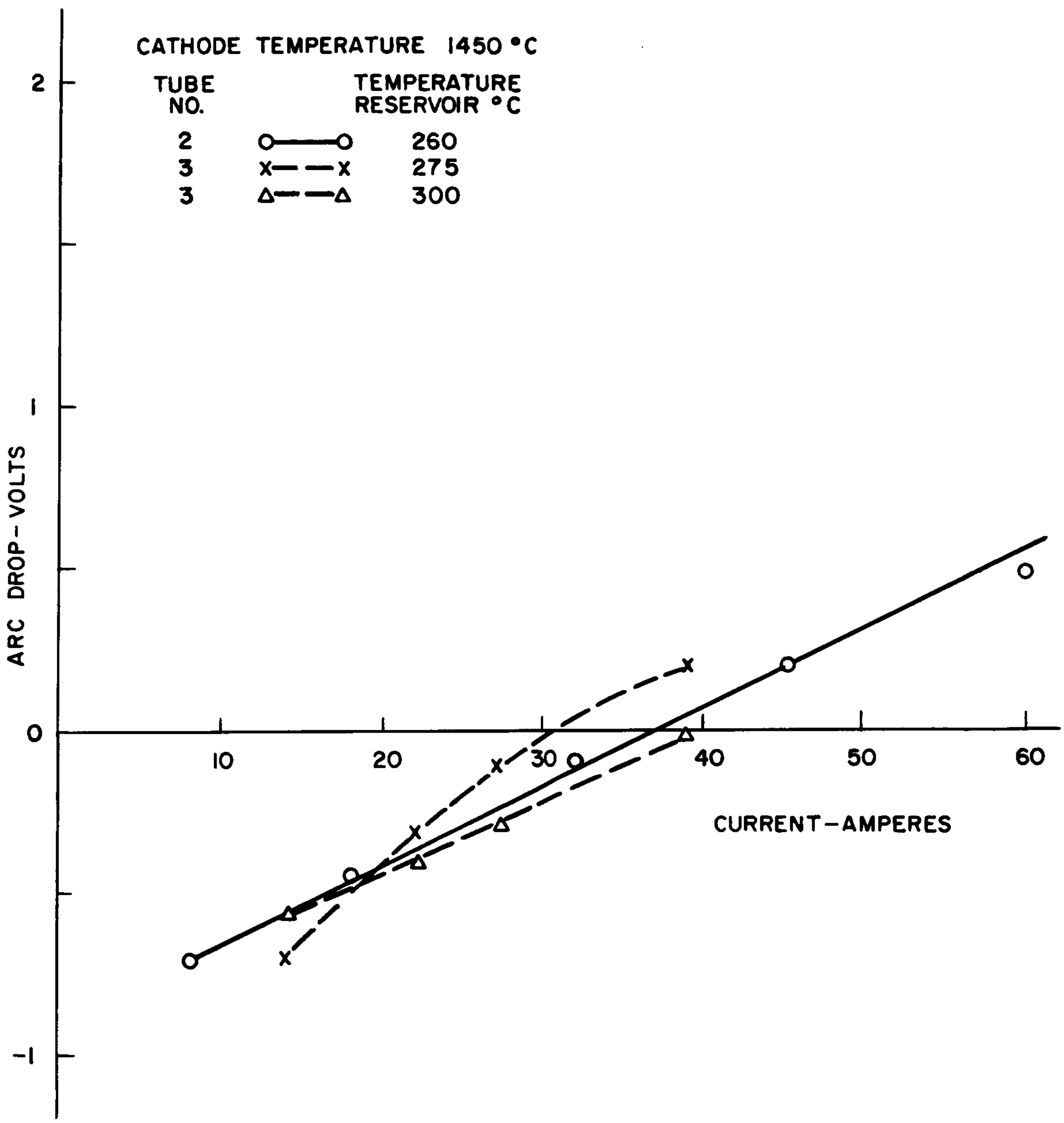

Figure 10 - Peak Tube Drop Versus Peak Current for Type Z-7009, Tube Nos. 2 and 3, Cathode Temperature 1450°C

Figure 11 illustrates inverse-current measurements taken on Type Z-7009, Tube No. 2. Inverse current became excessive when the anode temperature approached $500^{\circ}C$. The failure of the curves to approach zero current at low temperature indicated that the tube exhibited a leakage path (probably cesium) of about 300 ohms. The data is limited to peak inverse voltages of 140 volts because inverse breakdown occurred at 150 volts. Assuming a temperature drop of about $100^{\circ}C$ between a heat sink external to the tube and the hottest part of an electrode connected to the heat sink, an arbitrary rating of 125 volts inverse and $350^{\circ}C$ ambient might be applied to this particular diode.

It is of interest to contemplate how poor an emitter, an anode, or grid surface must be to prevent spurious ionization. One estimate can be made by computing the saturation current realized from cesiated molybdenum at $500^{\circ}C$, these conditions corresponding to the runaway threshold of Type Z-7009, Tube No. 2. Although the work function of bare molybdenum is about 4.4, its work function when cesiated drops to about 2.0. The curves in Figure 12, drawn for Richardson's equation, indicate a saturation current of about 10^{-5} ampere per square centimeter. This would imply the necessity of keeping anode and grid emission to a fraction of a microampere per square centimeter if spurious ionization is to be avoided.

When a substrate material is coated with a thin layer of another material, the work function of the combination is generally different from the work functions of either of the individual materials. For example, cathode emission is enhanced by a layer of barium molecules on nickel, or by a layer of thorium on tungsten. When a monolayer of cesium resides on a refractory metal such as molybdenum or tungsten, both of which have work functions higher than 4.0, the work function of the combination is reduced to a value of 2.0 or lower.

Spurious emission from a grid or anode in a cesium tube cannot be predicted without an established relationship between the substrate work function and the cesiated work function over the range of interest.

Rasor and Warner[1] attempted to establish such a relationship. Figure 13 displays a family of curves computed for this relationship. It may be

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1. Rasor, N. J., Warner, C., Correlation of Emission of Processes for Adsorbed Alkali Films on Metal Surfaces, Journal of Applied Physics, Volume 35, No. 9, September 1964, pp. 2589-2600.

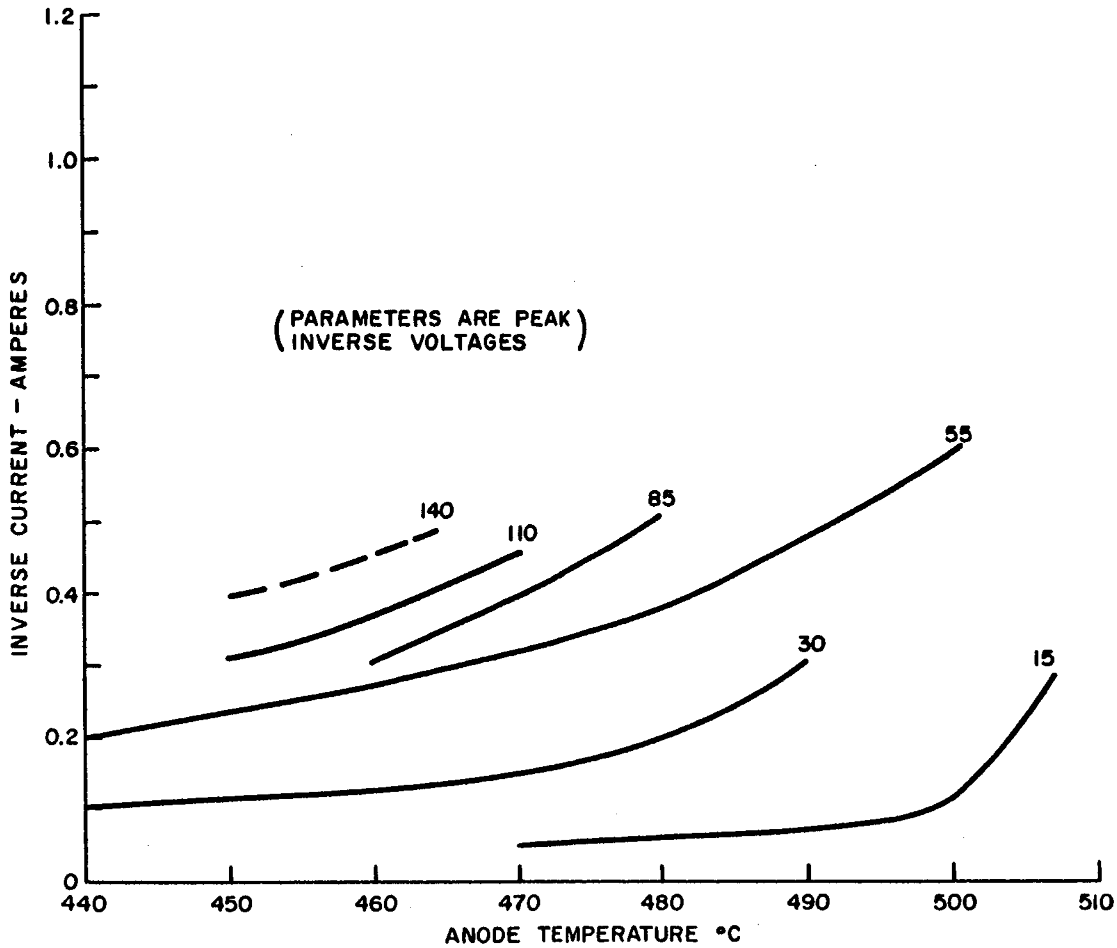

Figure 11 - Inverse Current Versus Temperature as a Function of Inverse Voltage

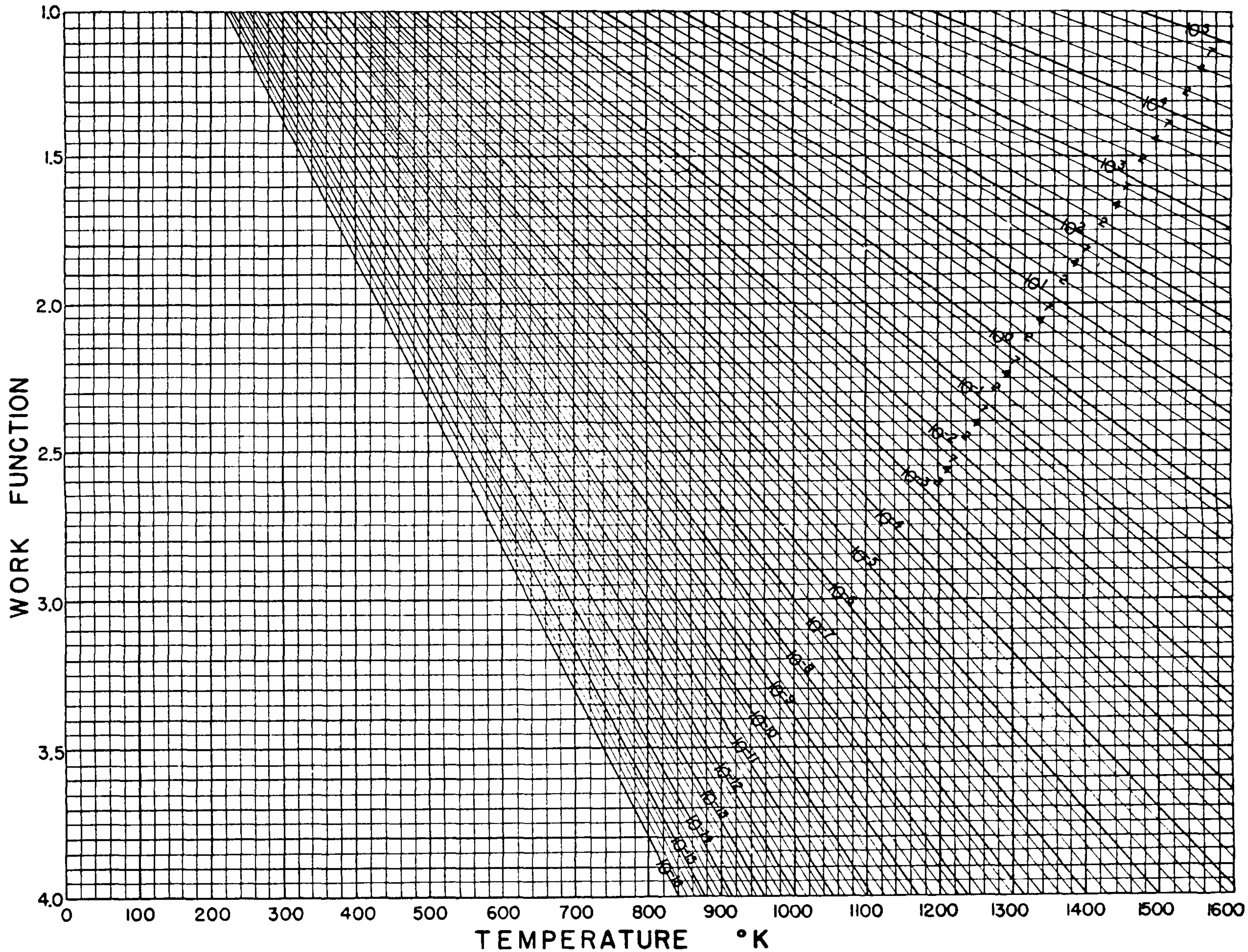

Figure 12 - Relation between Work Function, Temperature and Saturation Emission (Richardson's Equation)

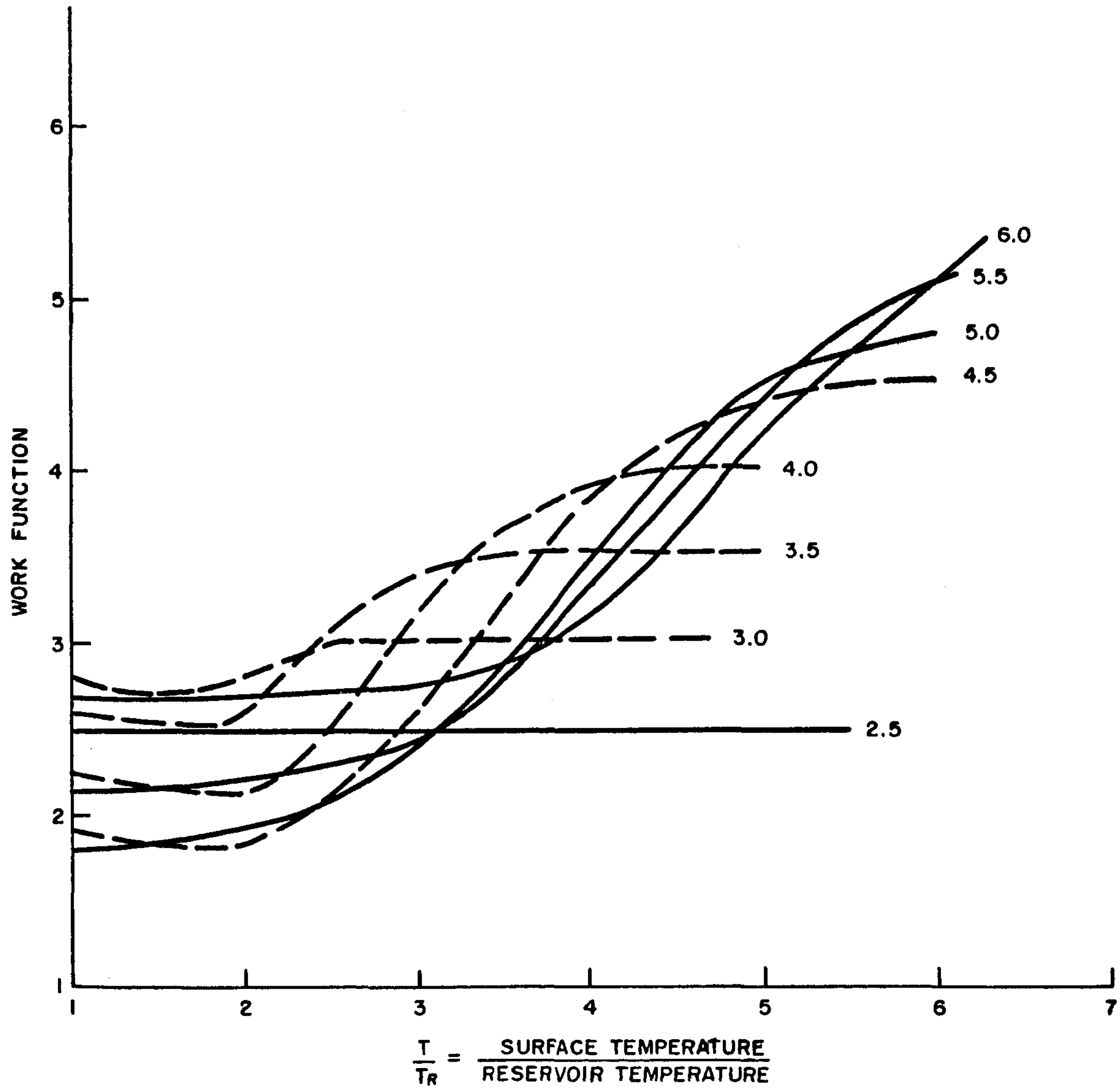

Figure 13 - Cesiated Work Function Versus Surface Temperature with Substrate Work Function as Parameter

noted from Figure 13 that for a low substrate work function, the cesiated work function remains the same, but as the substrate work function increases through the range of 3.0 to 5.0, the cesiated work function becomes lower. Therefore, the highest cesiated work function corresponds to a substrate work function of midvalue, about 3.0 to about 3.5. By combining the information given in Figures 12 and 13, a new series of curves may be drawn. These curves (Figures 14, 15, 16, and 17) illustrate the relationship between saturation current and substrate work function. For convenience, the same data is presented in Figure 18 in terms of cesiated emission versus bare substrate work function for the temperature range which is pertinent to a tube working into a 600°C heat sink.

From Figure 18, it is obvious that a work function of 3.0 would be preferable for the anode or grid surfaces. While a substrate work function of 6.0 would also be fairly good (for low emission), few conductors have such a high work function. Platinum has a work function range of 4.7 to 6.3, depending upon the exact crystallographic arrangement at its surface. However, platinum does not seem dependable, because if its work function decreased to 4.7, it would become an excellent emitter.

As a result of the above study, two materials were chosen for evaluation, namely zirconium carbide and the element hafnium, which have work functions of 3.1 to 3.5, respectively. While zirconium carbide has the preferable work function, it is subject to some degree of dissociation which would cause a cesiated work function lower than predicted.

Two tubes (Type Z-7009, Nos. 7 and 8) were constructed, in which the molybdenum anodes were coated (by a plasma jet spraying process) with zirconium carbide and hafnium, respectively.

Emission data (Figure 19) was taken on Tube No. 7 to determine the most efficient cathode temperature. It can be seen that there is little change in tube drop as the cathode temperature is lowered from 1300 to 900°C. Thus from the standpoint of efficienty, it would appear wasteful to provide the extra power needed to heat the cathode to a temperature of 1200 to 1300°C.

An analysis of efficiency may be made by:

1. Measuring the relation of heater power to cathode temperature. This constitutes an external power loss.

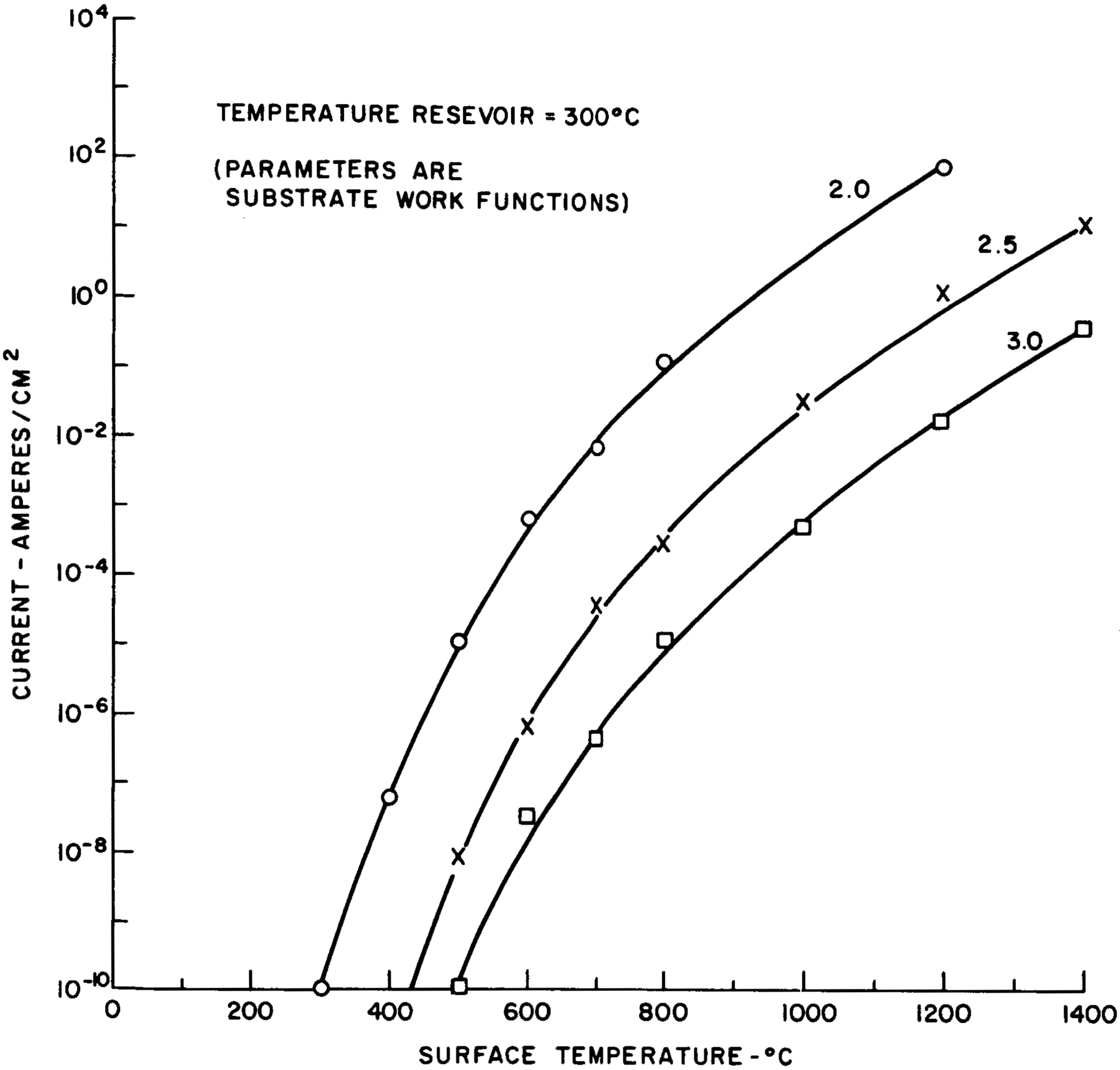

Figure 14 - Cesiated Emission Curves for Low-Range Bare Work Functions

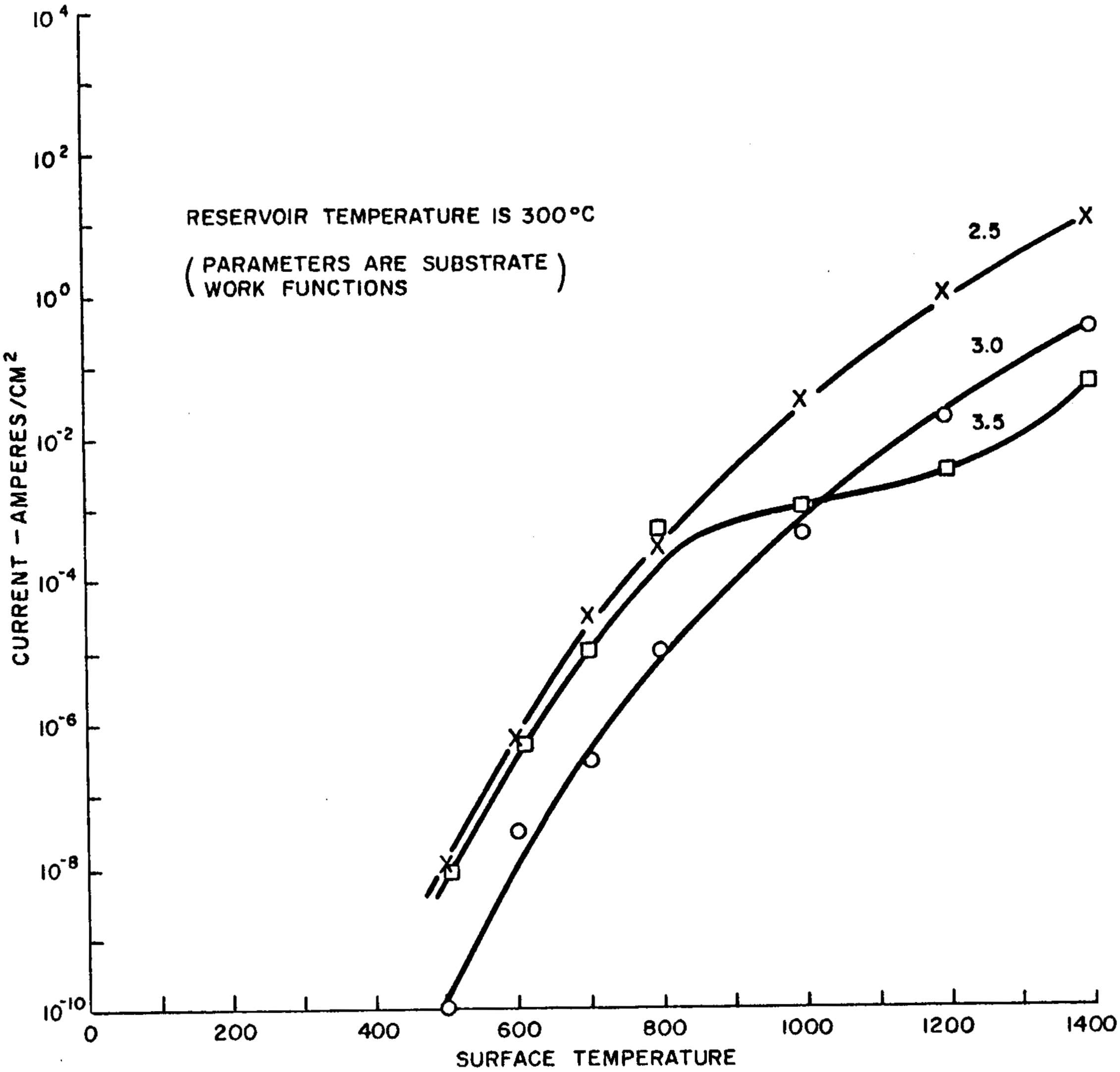

Figure 15 - Cesiated Emission Curves for Middle-Range Bare Work Functions

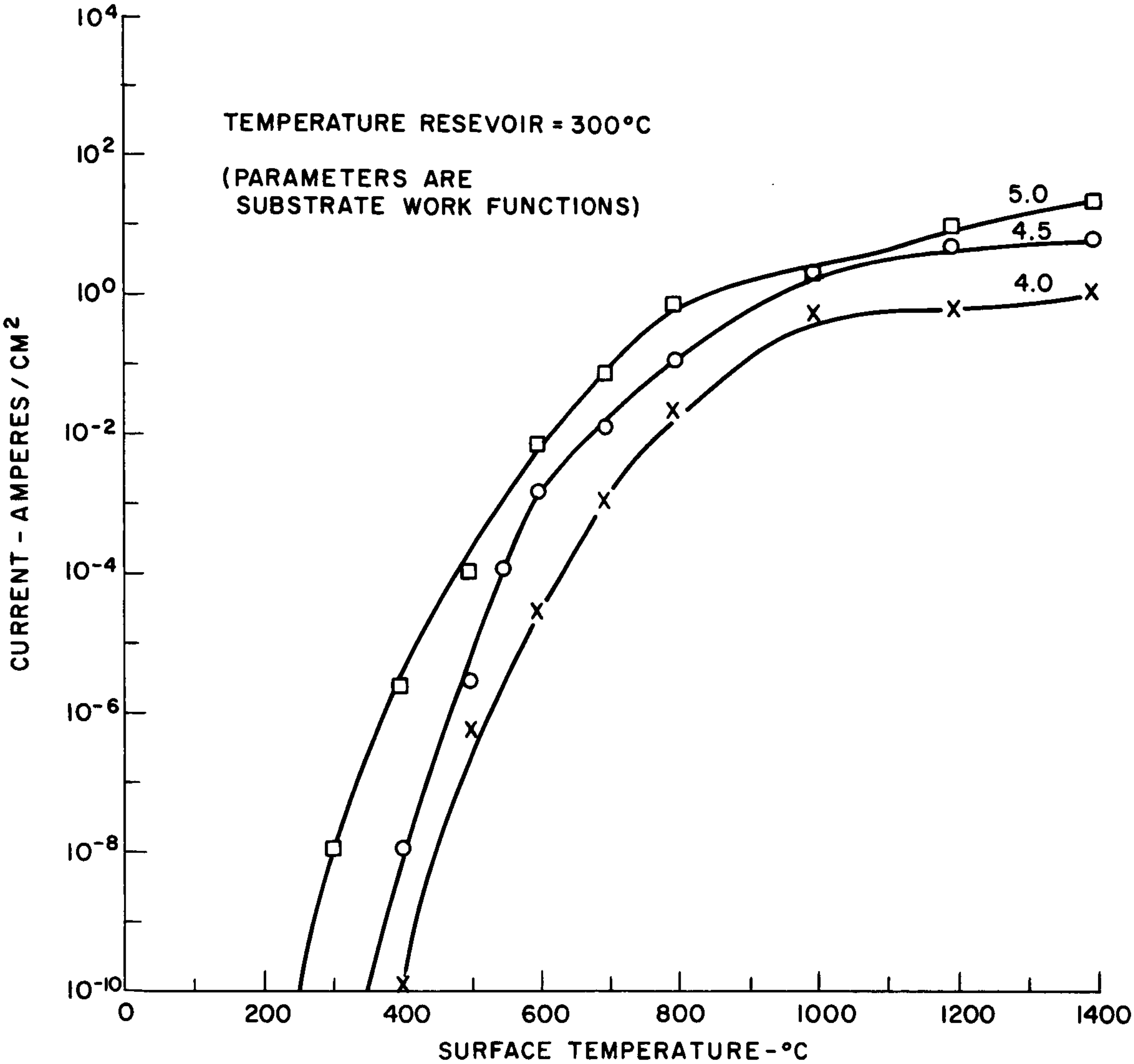

Figure 16 - Cesiated Emission Curves for Middle-to-High-Range Bare Work Function

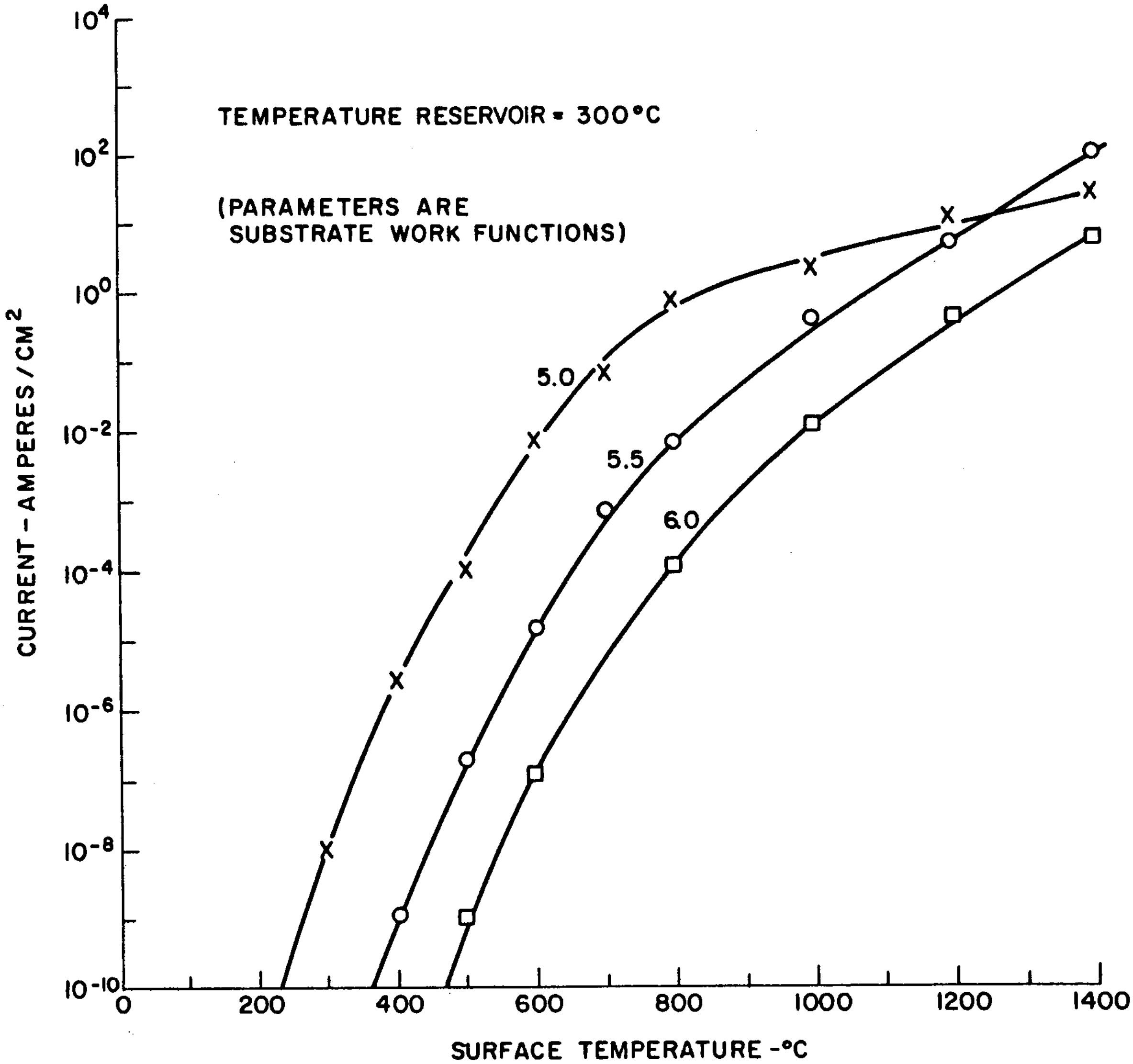

Figure 17 - Cesiated Emission Curves for High-Range Bare Work Functions

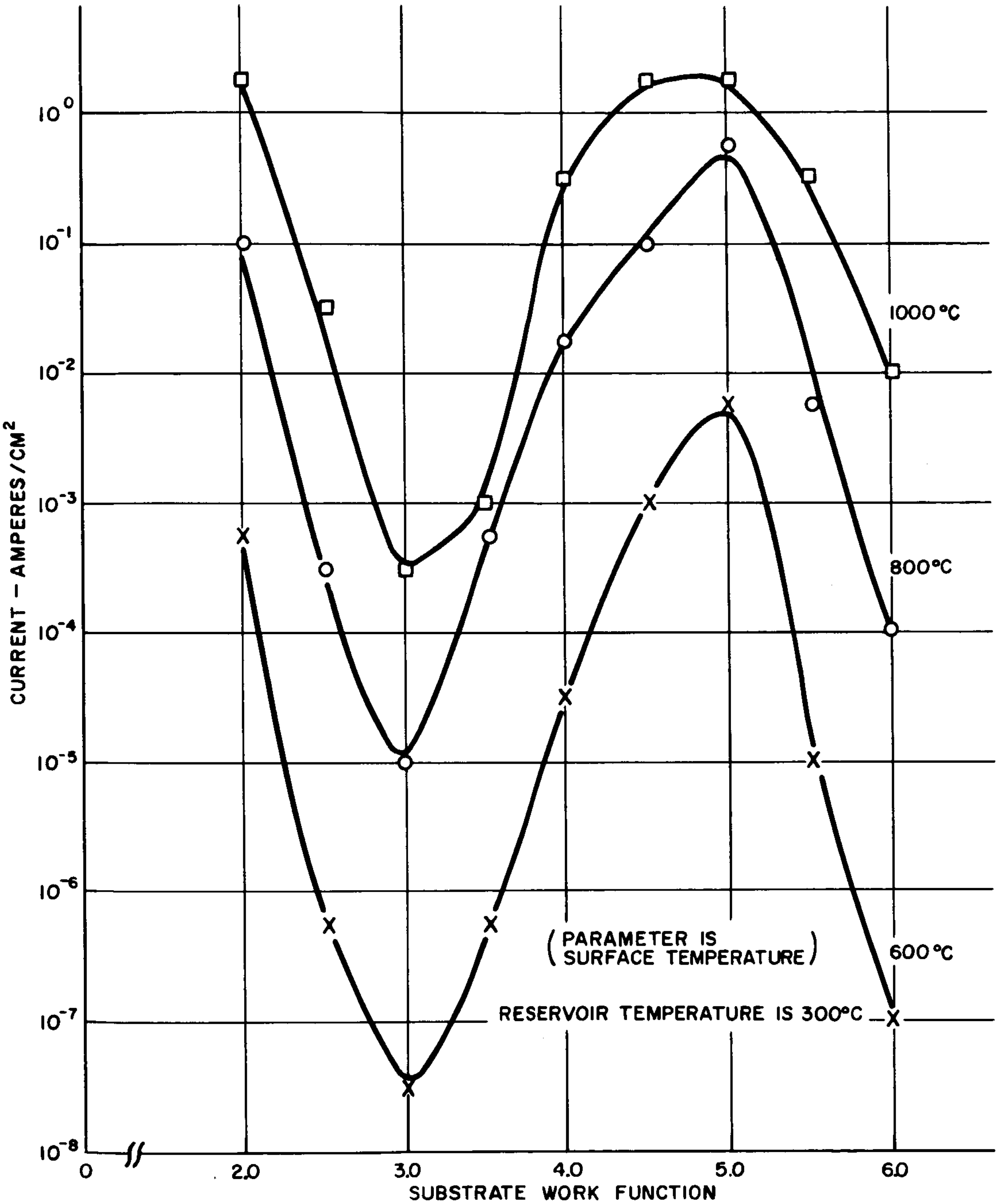

Figure 18 - Cesiated Emission Versus Substrate Work Function

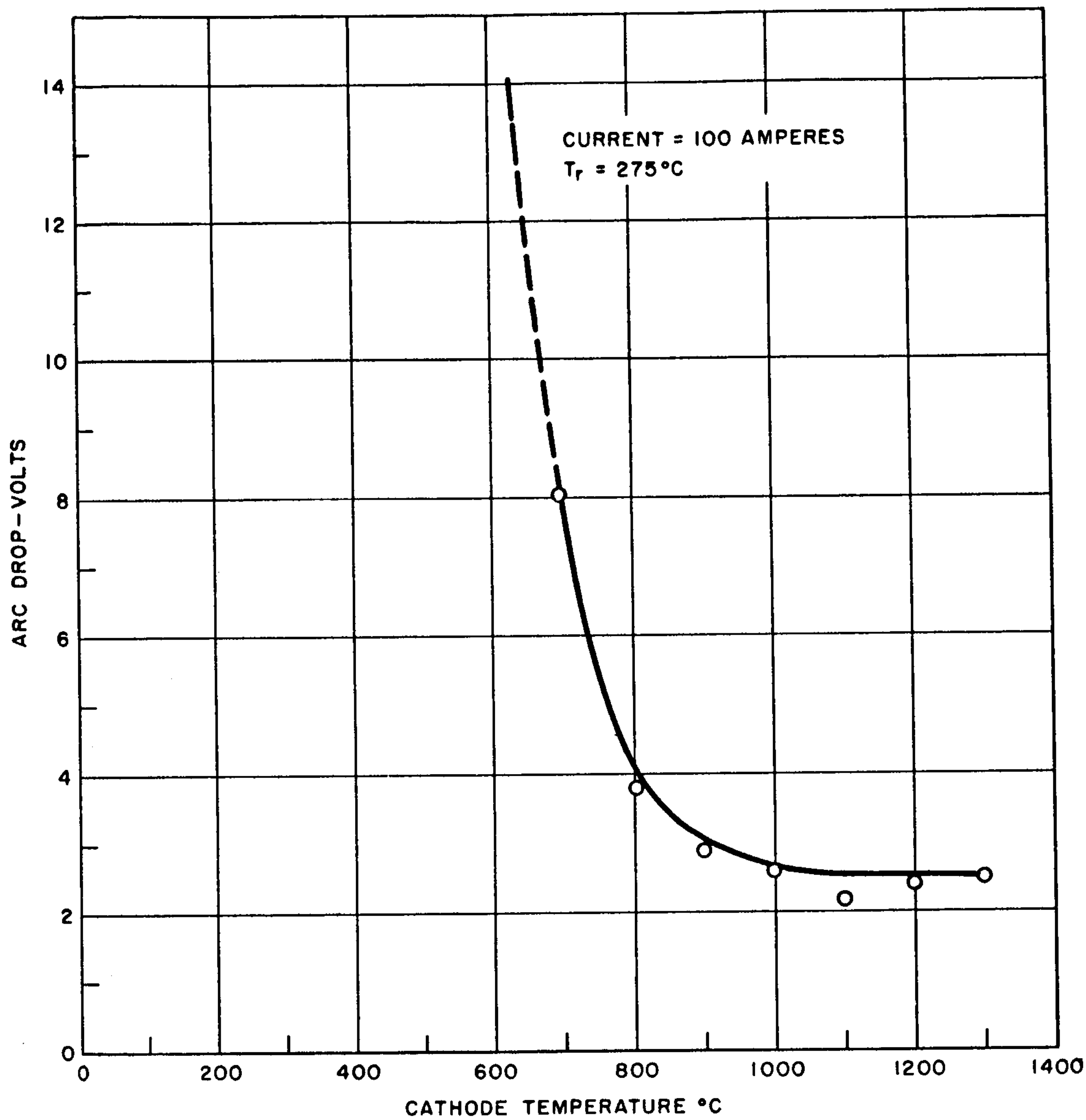

Figure 19 - Peak Drop Versus Cathode Temperature, Type Z-7009, Tube No. 7

2. Calculating an internal power loss, from the curve of Figure 19, multiplied by an assumed average current of fifteen amperes (the Phase I current level objective).

3. Obtaining the total power loss, which is equal to the sum of the internal and external losses.

Figure 20 exhibits, as a function of cathode temperature, the component and total losses. As can be seen from Figure 20, the most efficient point of operation occurs at a cathode temperature of 800°C. In practice, it would be advisable to operate the cathode at about 900°C to allow for variations between tubes, as well as for electron cooling at the cathode, which produces a power loss of I_b (W.F. + 2 KT/e), where:

W.F. = work function of the cathode in volts

K = Boltzman constant = 1.3708×10^{-23} watt-second/degree K

T = cathode temperature in degrees K

e = charge of electron = 1.590×10^{-19} coulomb

Since the 2 KT/e term is only about 0.1 volt in magnitude, it may be neglected without serious error, yielding I_b (W.F.) as the approximate power loss due to electron cooling.

The inverse voltage characteristic of the Zr C coated anode (Tube No. 7) showed no improvement over the case for bare molybdenum, Figure 21.

Hafnium (Tube No. 8) showed some improvement over bare molybdenum although not a significant amount, Figure 22. A degradation in inverse-voltage capability as a result of thermal emission occurred at an anode temperature of 410°C. This compares with a corresponding anode temperature of 380°C for the case of an uncoated molybdenum anode. Tube No. 8 was studied through a cesium reservoir temperature range of 300 to 125°C, corresponding to a pressure range of 1200 to 3 microns. At the low end of the range, there was an improvement in the inverse-voltage characteristic, since 560 volts inverse could be sustained at an anode temperature of 620°C. This is of academic interest only because the cathode emission is restricted to very low current levels when the cesium pressure is low enough to permit this gain.

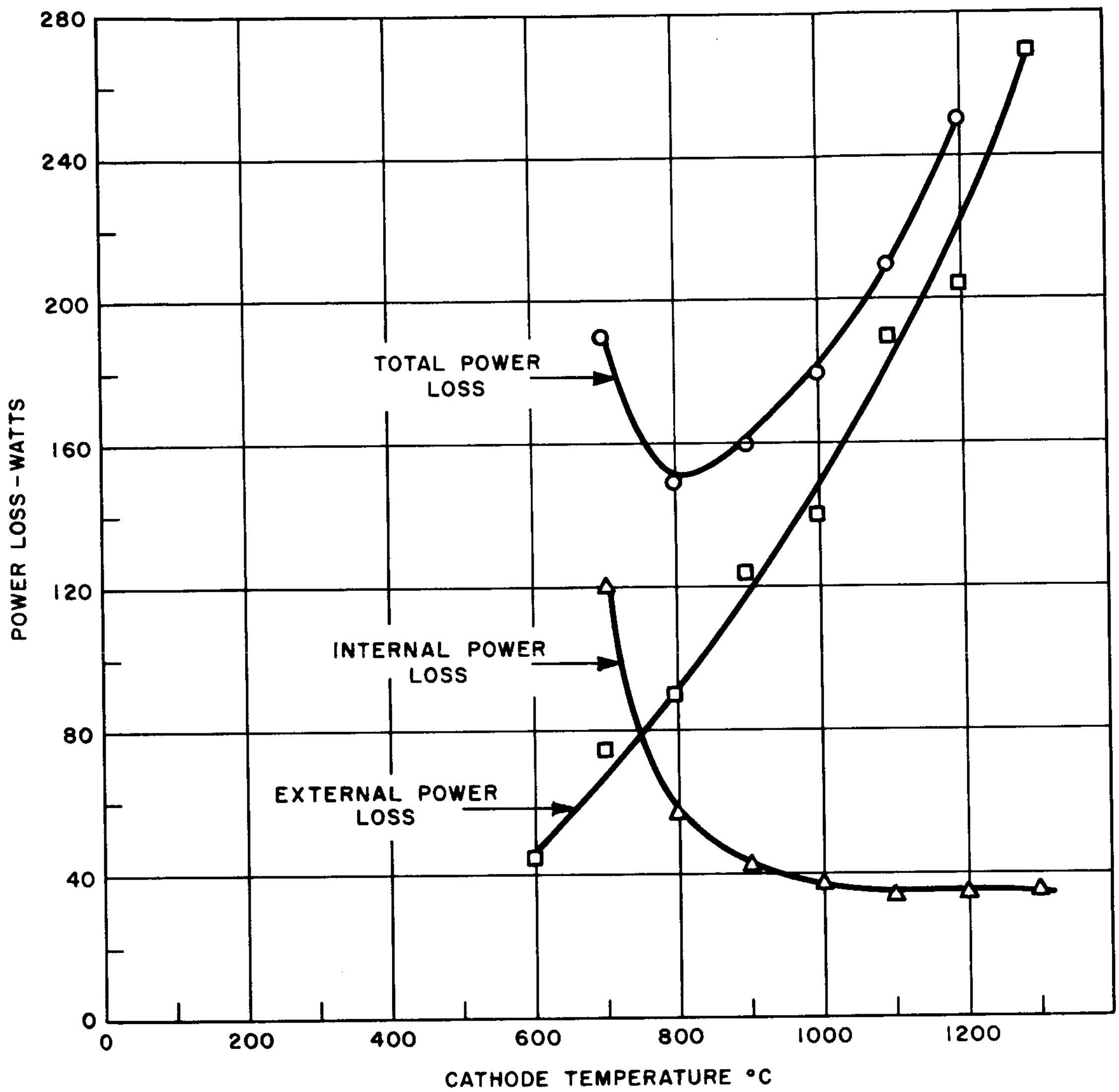

Figure 20 - Power Loss Versus Cathode Temperature, Type Z-7009, Tube No. 7

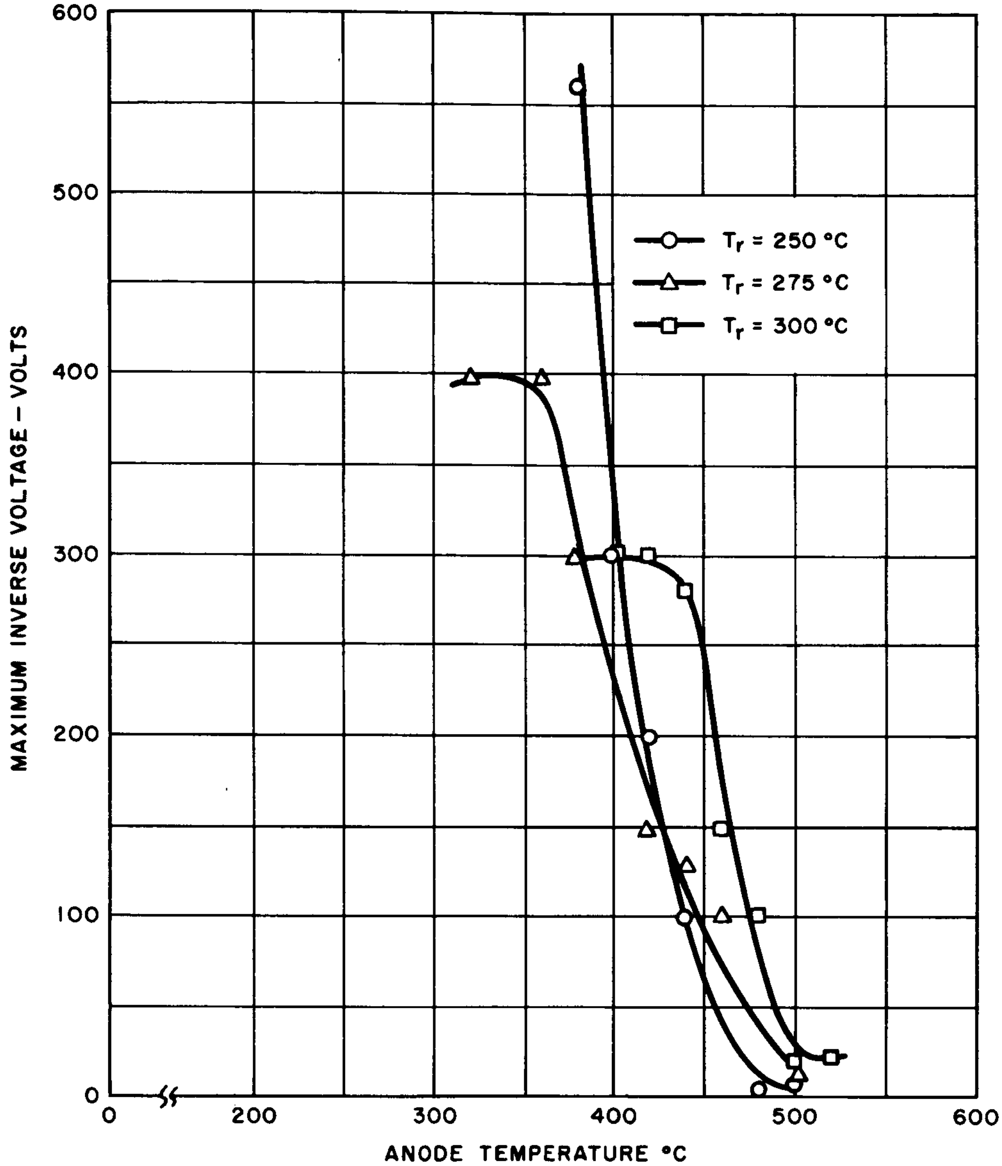

Figure 21 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 7

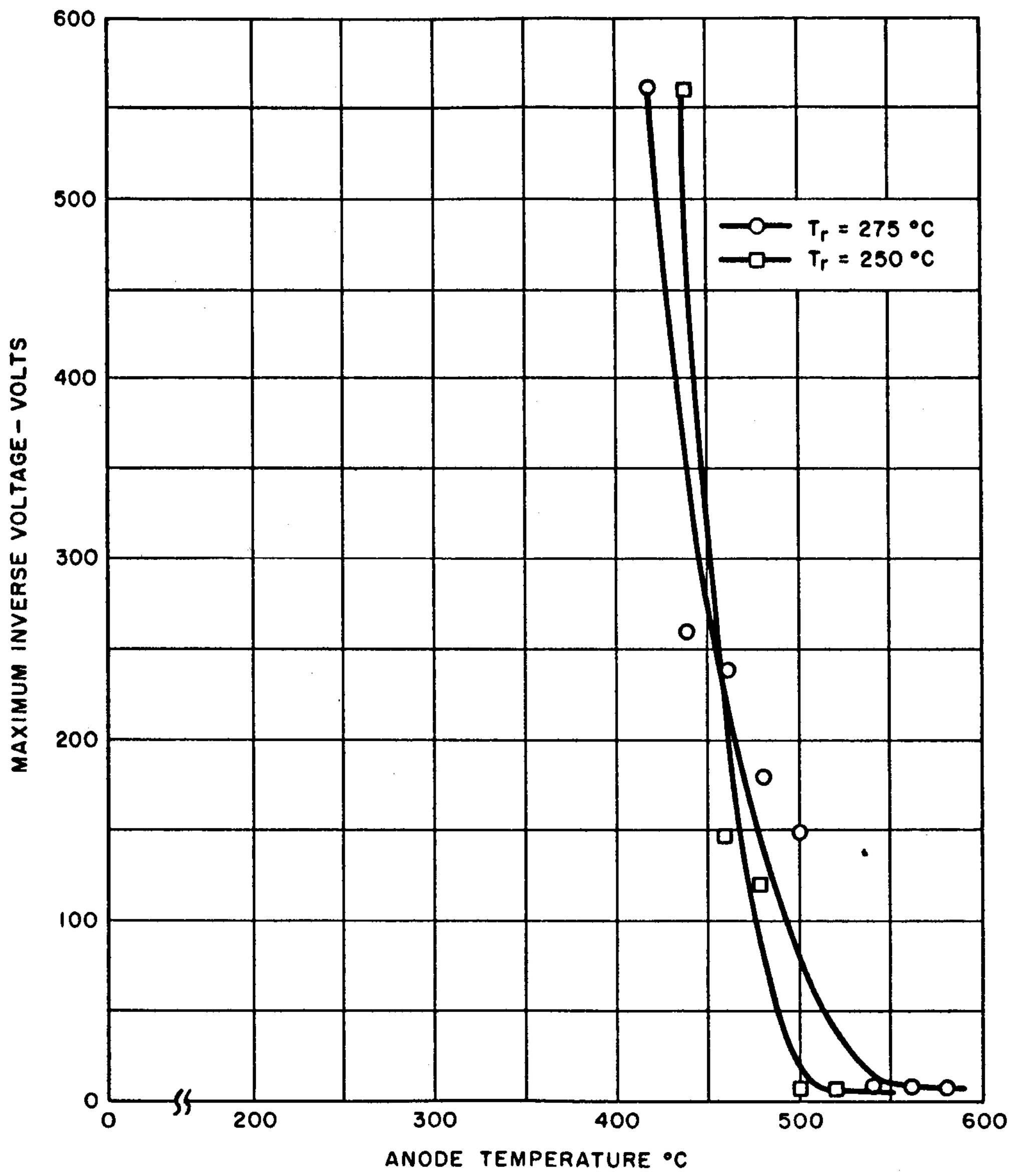

Figure 22 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 8

Like cesium, the other alkali metals -- rubidium, potassium, sodium and lithium -- and the alkali earths -- barium, strontium and calcium -- have the capacity of lowering the work function of a substrate material when deposited on the substrate in the form of a thin film. Because cesium has the lowest work function and the lowest ionization potential of all the alkali metals, it was deemed that a different alkali metal might produce a less efficient emitter and result in a tube with a lower anode emission at a given temperature. This presented the possibility of coupling a less efficient cathode with an anode that could be raised to a higher temperature before the occurrence of inverse voltage breakdown.

Type Z-7009, Tube No. 15, was made with a rubidium fill and yielded the emission data shown in Figures 23 and 24. A comparison between Figures 19 and 24 indicates that the rubidium tube had less efficient cathode emission, but its inverse-voltage characteristic (Figure 25) is not improved over that obtained with a cesium-filled tube.

Sufficient data was available for estimating the maximum ambient or heat-sink temperatures to which alkali-vapor tubes might be used. The maximum heat-sink temperature is considered to be the maximum permissible electrode temperature less the thermal drop between the electrode and the heat sink. For a structure of the type shown in Figure 26, and for the case of a 15-ampere tube, where anode dissipation might be in the order of 100 watts, it was computed that the thermal drop could be held to about 100°C. Thus, with this figure and the summary comparison of Figure 27, maximum heat-sink temperatures become:

Combination	Heat-Sink Temperature, °C
1. Molybdenum anode, cesium fill	280
2. Zirconium carbide anode, cesium fill	240
3. Hafnium anode, cesium fill	310
4. Molybdenum anode, rubidium fill	240

Because the preceding heat-sink temperatures were so far removed from the objective heat-sink temperature of 600°C, it appeared necessary to resort to a prepared cathode with lower efficiency, such as a barium or thoriated-tungsten cathode and a fill material other than an alkali metal. These aspects are discussed in the next section.

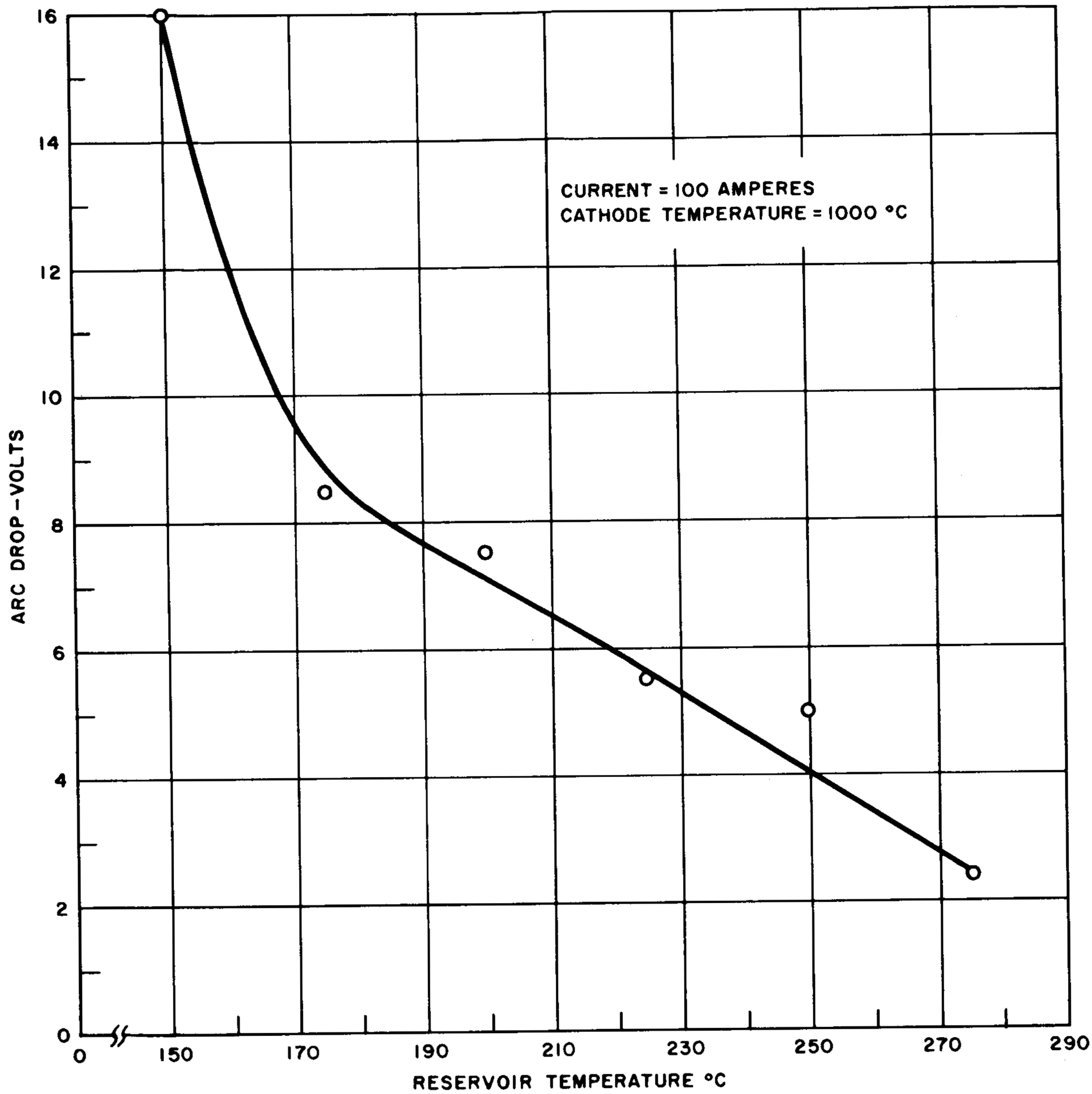

Figure 23 - Peak Drop Versus Reservoir Temperature, Type Z-7009, Tube No. 15

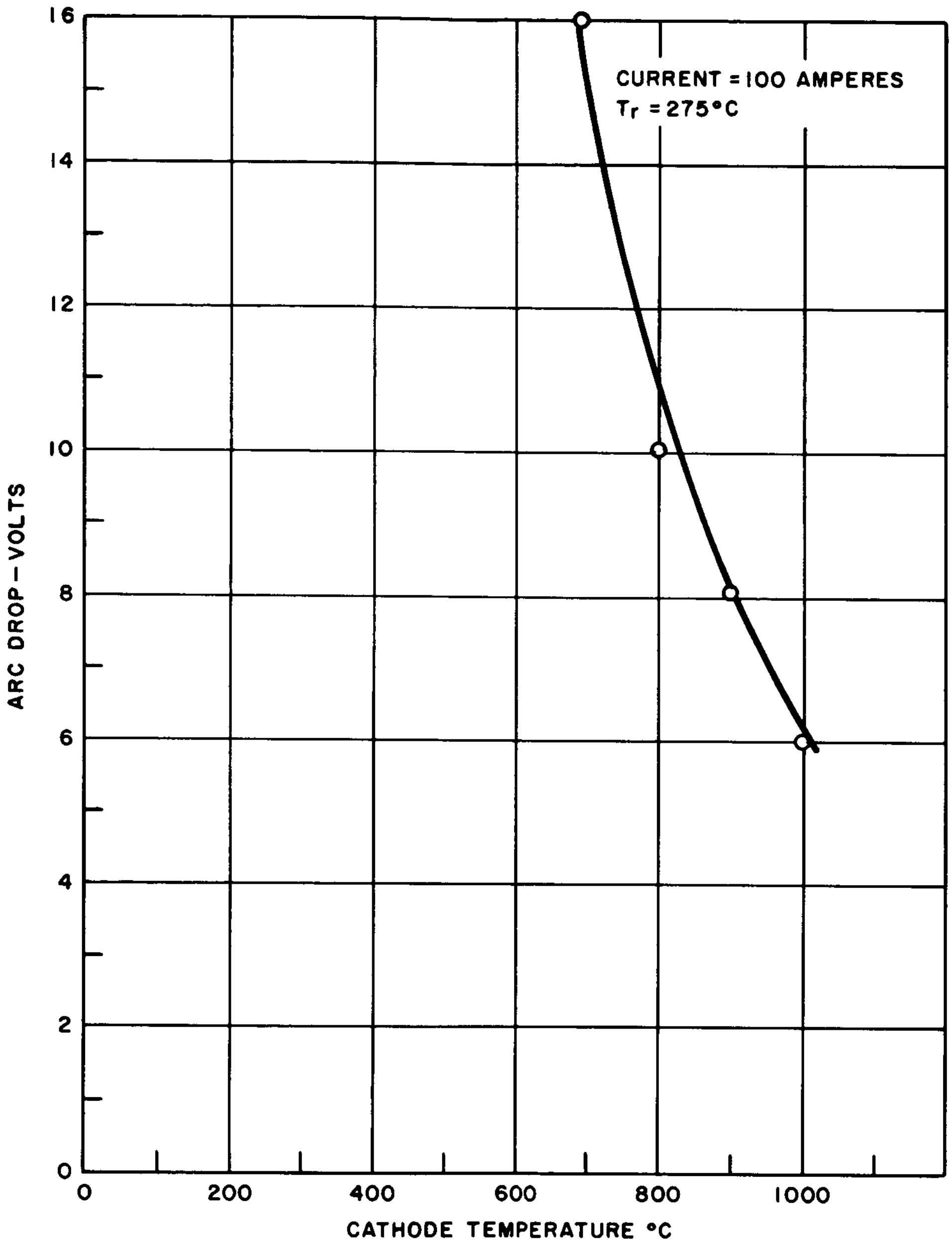

Figure 24 - Peak Drop Versus Cathode Temperature, Type Z-7009, Tube No. 15

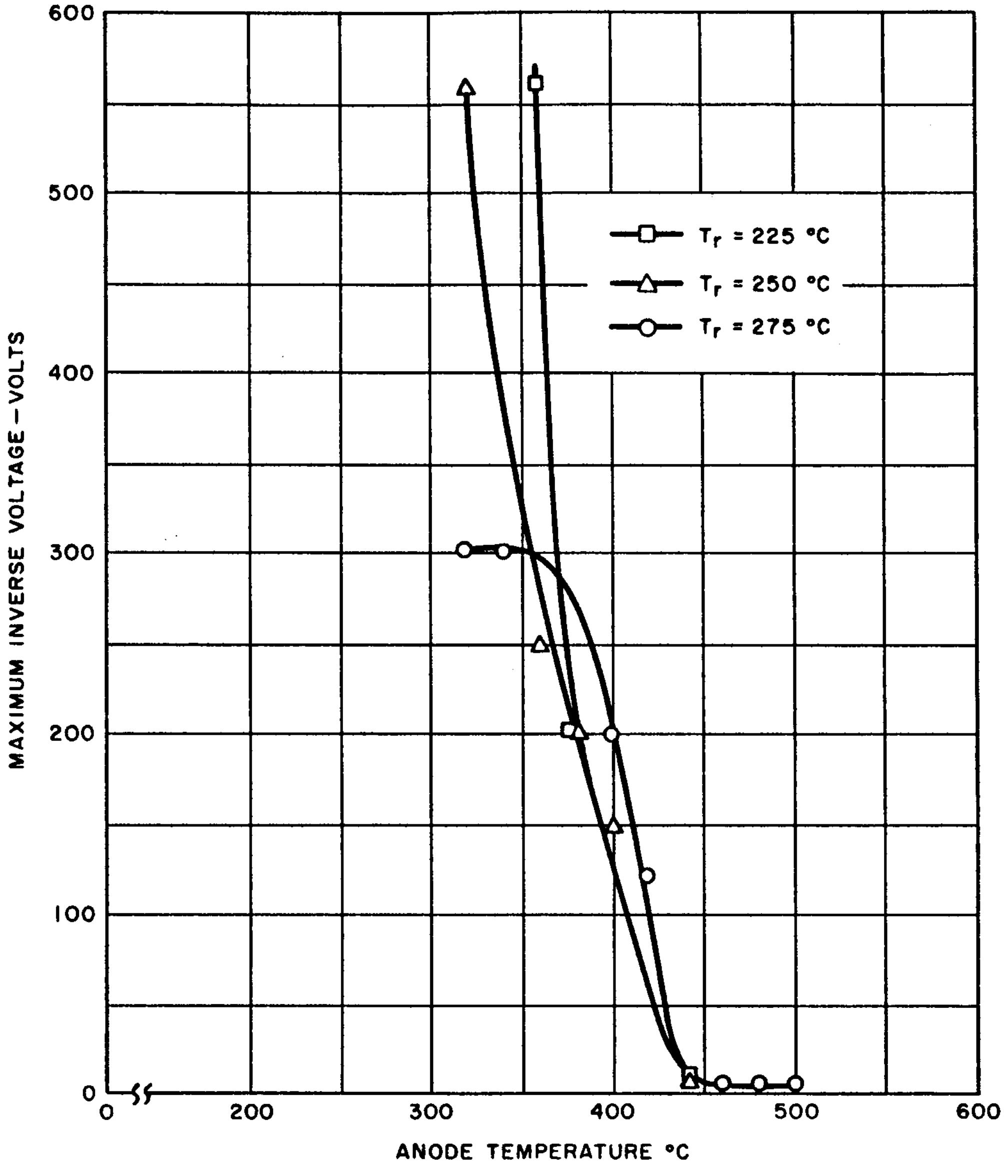

Figure 25 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 15

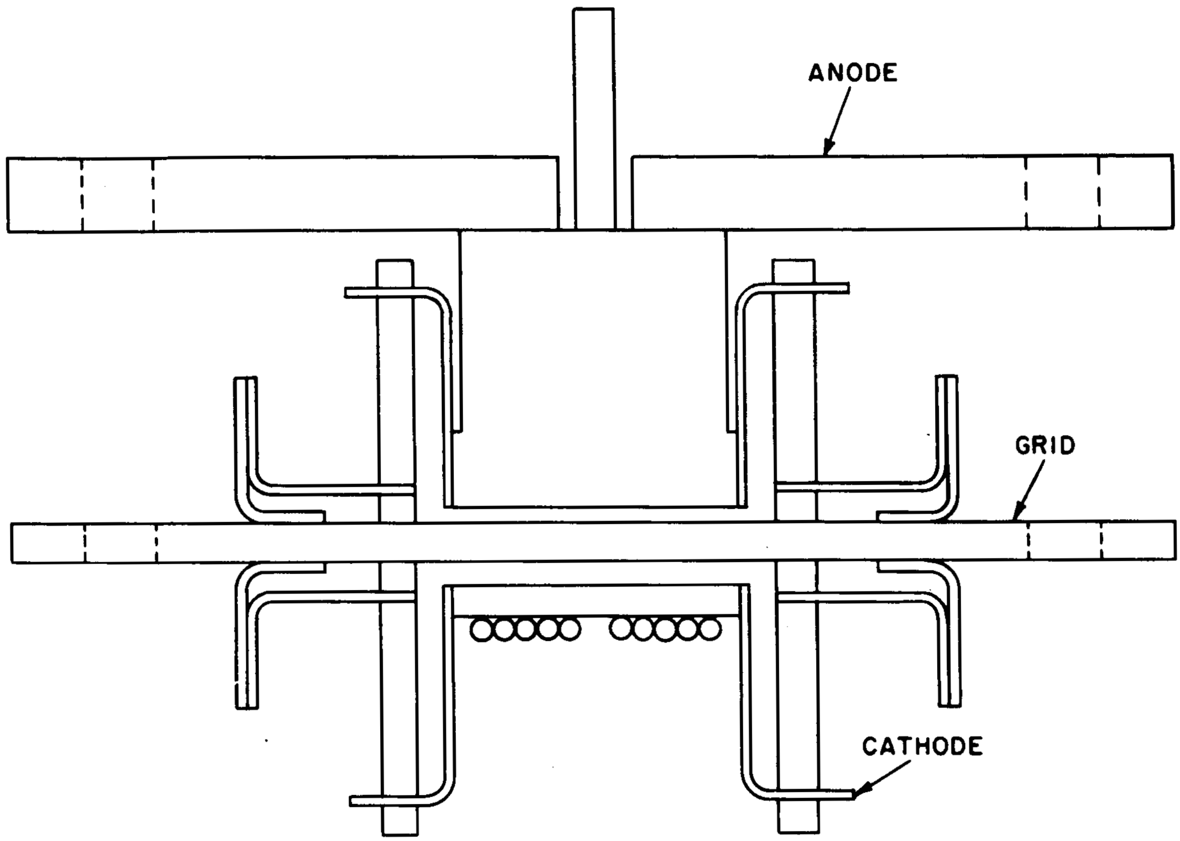

Figure 26 - Conceptual Design for High-Temperature Thyratron

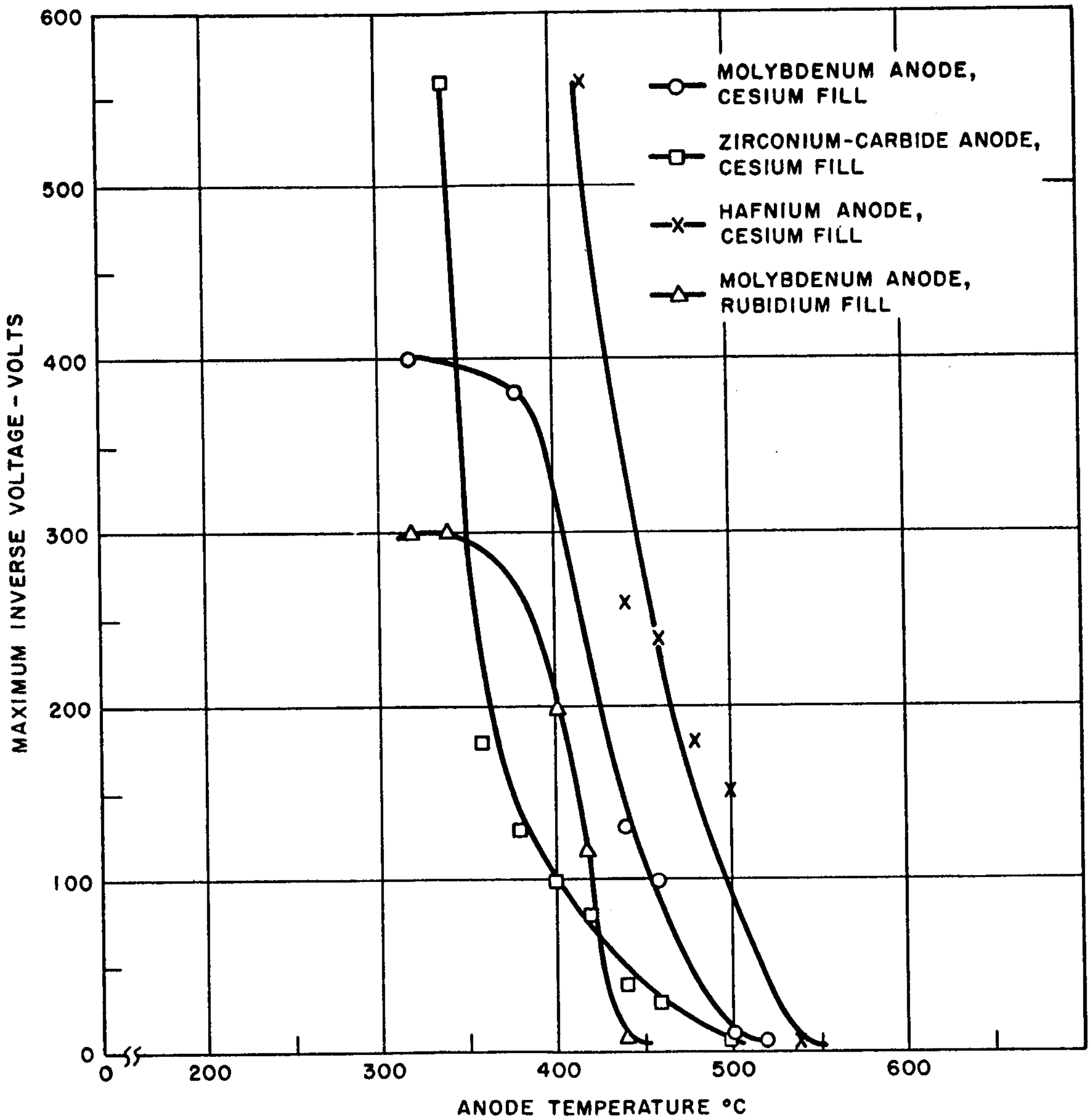

Figure 27 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature for Various Anode and Fill Combinations

OTHER VAPOR-FILL MATERIALS

At the beginning of the contract, a contemplated listing of possible cathode and fill combinations, in order of descending efficiency was as follows:

	Cathode	Fill
1.	Cesiated refractory metal	Cesium (high pressure)
2.	Barium	Cesium (low pressure)
3.	Barium	Thallium or equivalent
4.	Thoriated tungsten	Cesium (low pressure)
5.	Thoriated tungsten	Thallium or equivalent
6.	Tungsten	Cesium (low pressure)
7.	Tungsten	Thallium or equivalent

Because of the previously described temperature restrictions attending the use of alkali metals, a revised listing for a 600^{o}C environment would include only:

	Cathode	Fill
1.	Barium	Thallium or equivalent
2.	Thoriated tungsten	Thallium or equivalent
3.	Tungsten	Thallium or equivalent

"Thallium or equivalent", as used here, means one of four metals having vapor pressures between 10^{-2} and 1 torr in the temperature range of 600 to 800^{o}C, Figure 4. Two other important considerations for these materials are ionization potential and compatibility. The ionization potentials for the elements depicted in Figure 4 are as follows:

Thallium	6.1 volts
Lead	7.4 volts
Bismuth	8.0 volts
Antimony	8.5 volts

In each case, the minimum tube drop would be about a volt higher than the ionization potential.

The compatibility of the above metals with other materials commonly used in high-temperature tubes cannot be completely predicted. Phase diagrams or the constitution of binary alloys (to the extent that such information is available) can be used as a guide to the compatibility problem, but, as in the case of cesium, actual compatibility cannot be established without long-term testing.

THORIATED-TUNGSTEN DIODE

Of the three eligible cathode systems that might be used in a high-temperature tube, the barium cathode offers the least margin of safety with respect to spurious grid and anode emission. Therefore, the decision was made to evaluate thoriated tungsten initially. A feasibility tube was designed containing a special anode that fitted closely to a thoriated-tungsten cathode mounted on the bottom-end subassembly of a GL-6942 transmitting tube. The anode-cathode portion of the feasilibity tube, less bottom-end supports and seals, is shown schematically in Figure 28. The cathode has an area of two square centimeters, and in transmitting tube service such a cathode is considered capable of about five amperes average current. The tube was designed with an anode temperature of about 1000°C when the cathode is at the normal operating temperature of 1650°C. Thus, by merely controlling the cathode temperature, the anode temperature could be controlled to any temperature below 1000 degrees centigrade, permitting the establishment of a curve of maximum inverse anode voltage versus anode temperature. Since little experience existed in respect to operation of a thoriated-tungsten cathode in a low-pressure vapor or gaseous device, a possible compatibility problem was avoided in the first device (Type Z-7009, Tube No. 16) by filling it with 50 microns of xenon, one of the inert gases.

Initially, there was no inverse emission difficulty with an inverse anode voltage of 700 volts and an anode temperature of 1000°C. Since the anode could have become more heavily coated with thorium later in life -- but presumably never more heavily coated than the cathode surface itself -- it was assumed that meaningful information might be derived from measuring forward breakdown as a function of cathode temperature. The lowest cathode temperature observed, which permitted forward breakdown (with 700 volts applied), was 950°C. Since this temperature is above the temperature at which electrodes must operate in a tube having a 600°C environment, it was felt that feasibility from the standpoint of temperature was demonstrated.

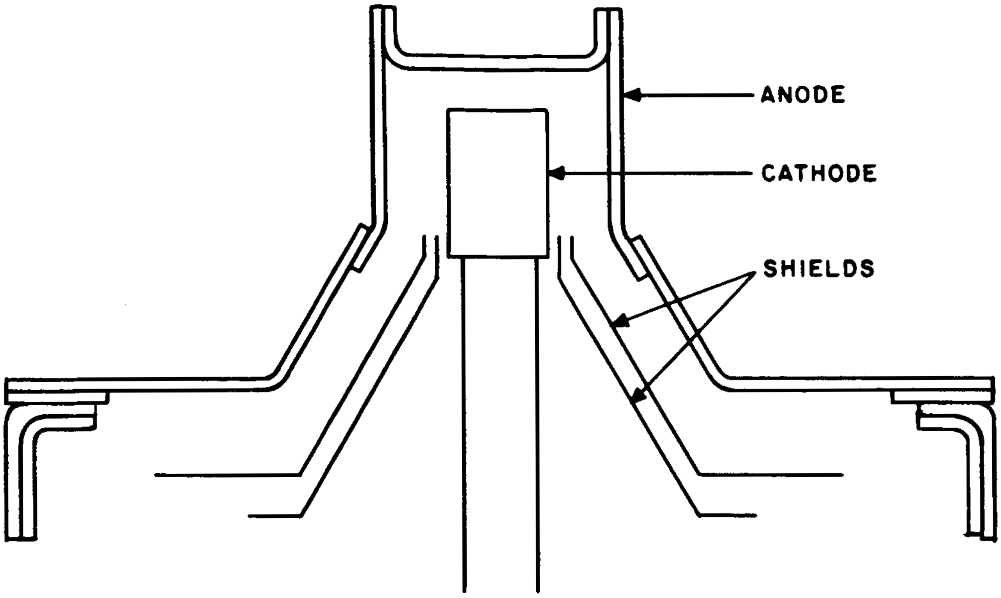

Figure 28 - Schematic of Test Vehicle, Design E

Initial emission curves for Tube No. 16 are given in Figure 29. The tube was operated for 590 hours at an average current of one ampere, during which time the cathode emission gradually slumped, as shown in Figure 30. Inverse anode emission characteristics were checked a number of times during the run, and at no time was there evidence of arc-back with the anode temperature at 1000°C. No forward breakdown was observed unless the cathode temperature exceeded 900°C.

Figure 31 depicts a thyratron structure intended to be capable of 15 amperes, average. The cathode is a spiral-shaped thoriated-tungsten filament, having an area of about 20 square centimeters. It would operate with an input of 2.5 volts and 300 amperes. Although heat-sink details are not shown, the heavy disc construction should permit the efficient removal of heat from the interior of the tube to the heat sink.

THALLIUM-FILLED DIODE

Because life test of the thoriated-tungsten cathode with xenon fill was not encouraging, it was considered inadvisable to proceed with a test of thoriated tungsten in a thallium atmosphere. Consequently, Type Z-7009, Tube No. 19, was made with the combination of thallium fill and a barium-system cathode. This tube contained wide welding flanges (Figure 32) to permit the tube to be taken apart for repair, inspection, or replacement of parts. The cathode was a five-square-centimeter barium dispenser type, and the reservoir and thallium-filled pellet were located in a tubulation atop the anode.

At a cathode temperature of 1100°C, the tube could be operated continuously at an average current of two amperes, with a voltage drop of about eight volts. At higher cathode temperatures, 50 to 60 amperes peak could be drawn from the cathode with reasonably low voltage drops, Figure 33. In the interest of low cathode evaporation, 1100°C was chosen as the operating temperature.

With the reservoir running hotter than the tube wall, the tube-wall temperature established the thallium vapor pressure within the tube, Figure 34. Thus, the tube drop was high when the wall temperature was below 580°C, corresponding to the low equilibrium thallium vapor pressure of four microns.

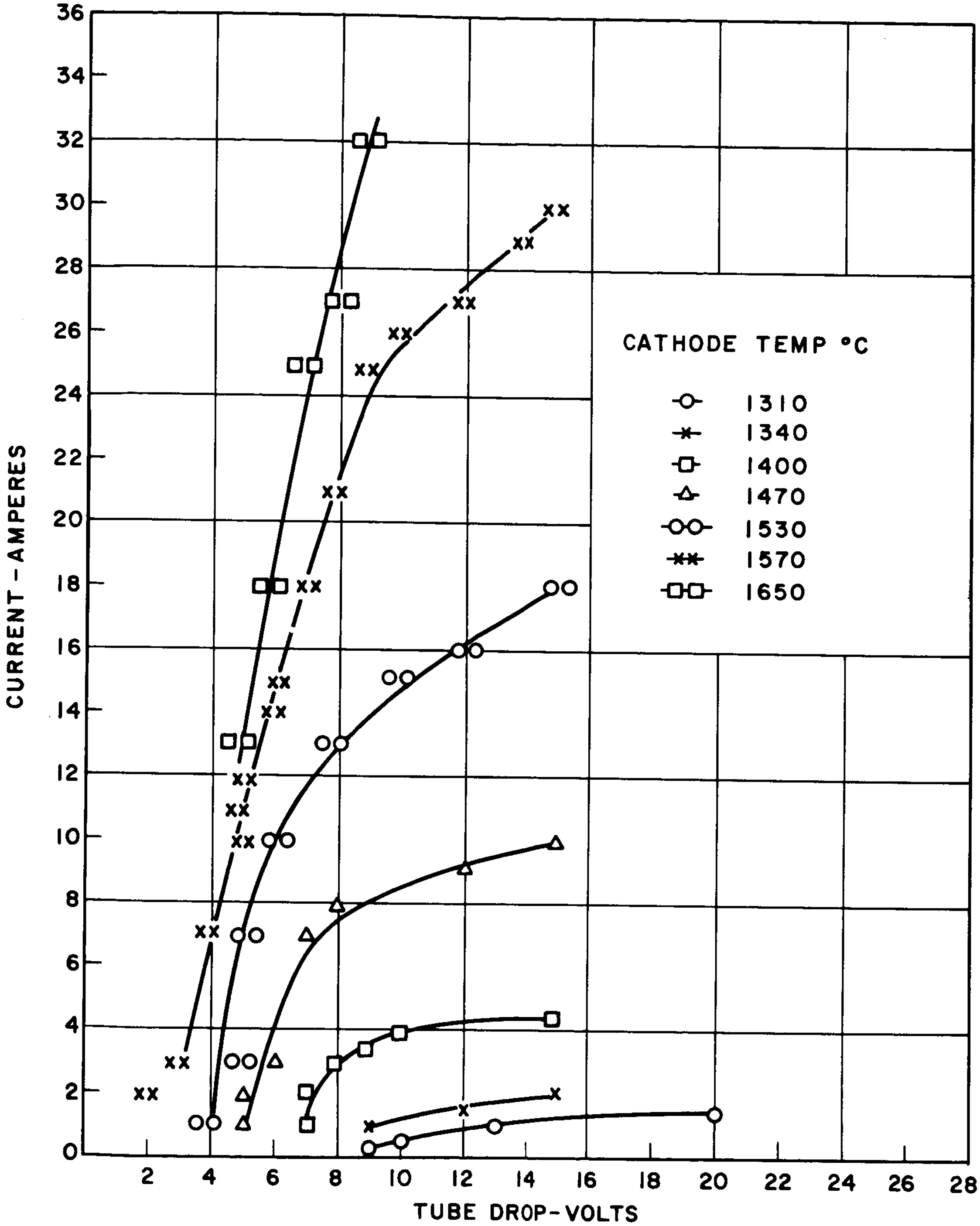

Figure 29 - Current Versus Voltage, Type Z-7009, Tube No. 16

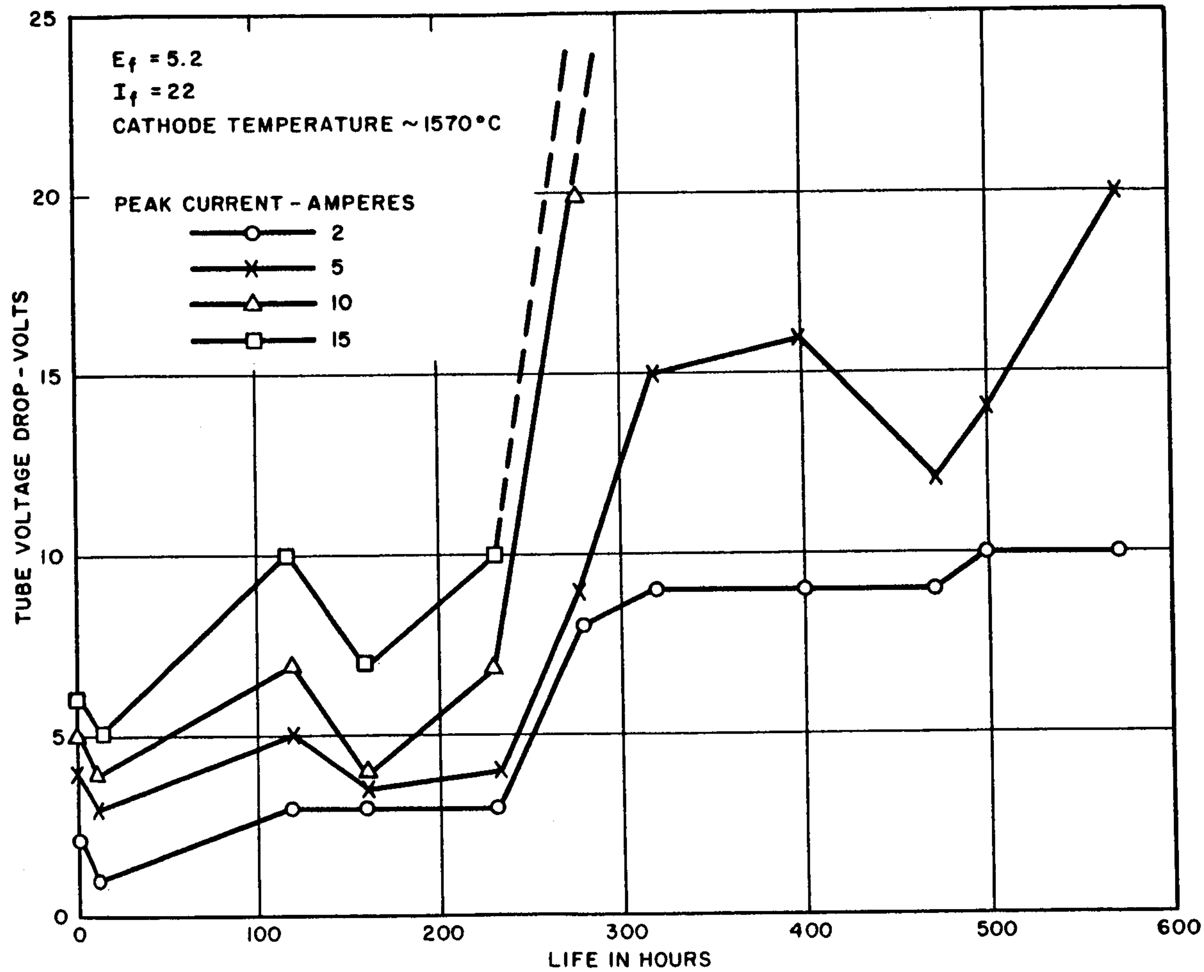

Figure 30 - Tube Drop Versus Life in Hours, Type Z-7009, Tube No. 16

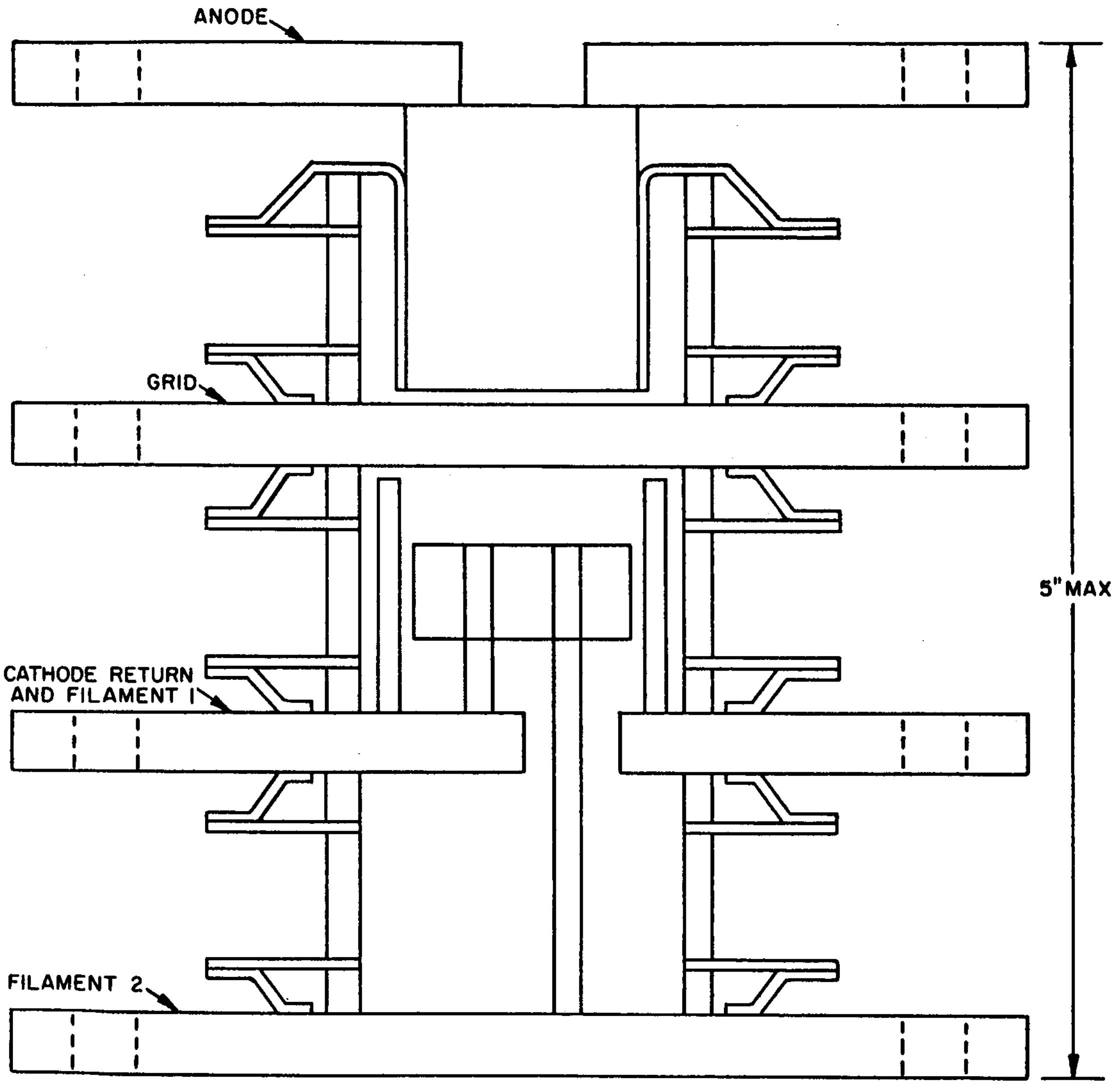

Figure 31 - Conceptual Design F for High-Temperature Thyratron

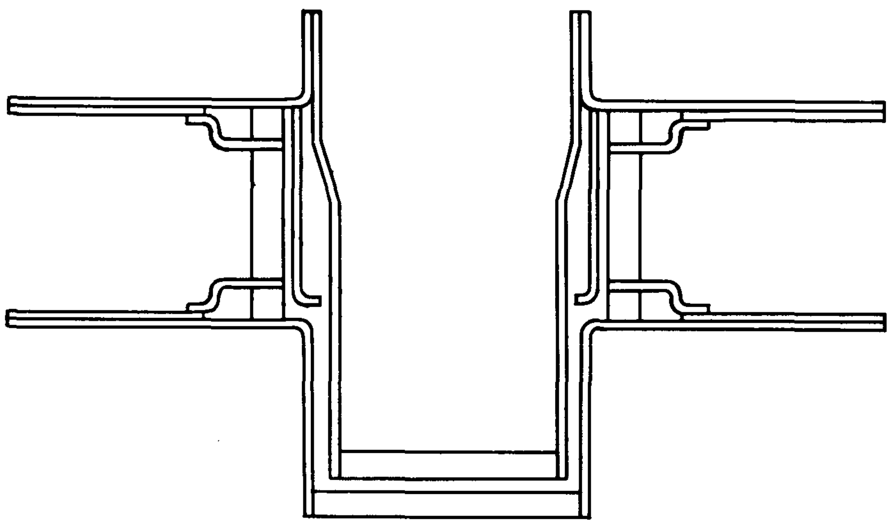

Figure 32 - Schematic of Test Vehicle, Design J

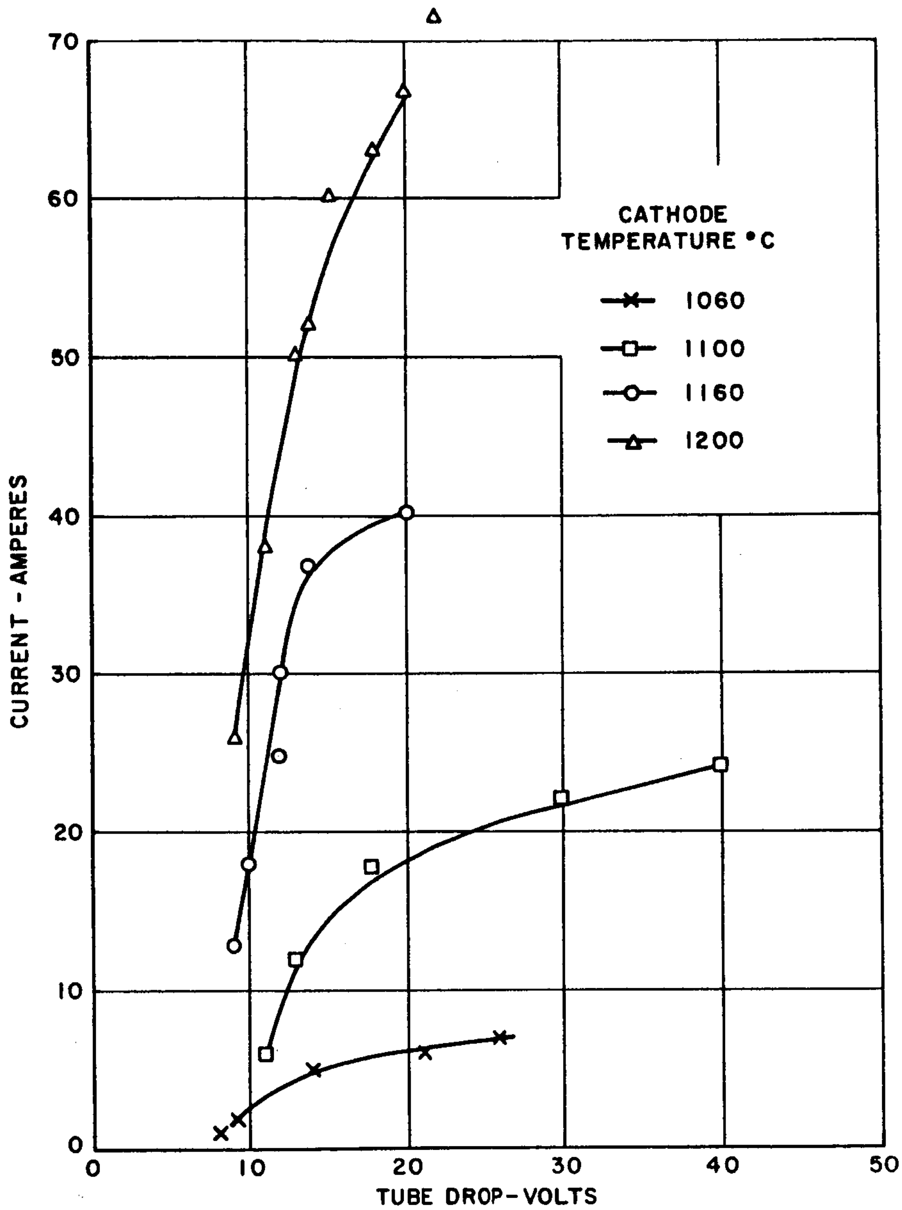

Figure 33 - Current Versus Voltage, Type Z-7009, Tube No. 19

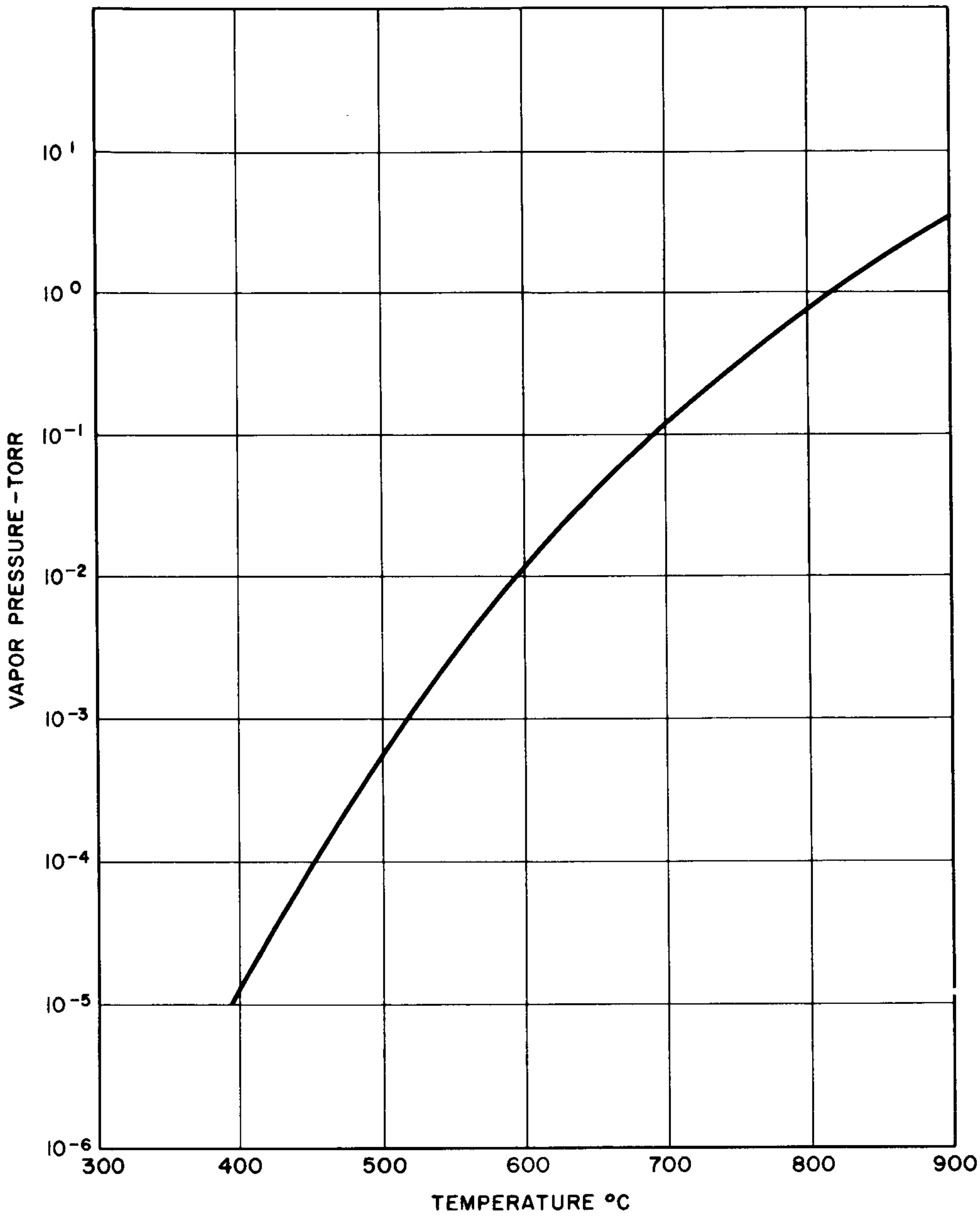

Figure 34 - Vapor Pressure Curve for Thallium

There was evidence of some reaction between thallium and barium, at wall temperatures of 650°C or higher, corresponding to 30 microns of vapor pressure, for at this temperature the tube drop increased when high current densities were drawn from the cathode. At low current densities and at 650°C, the tube drop remained low, but at any current density the tube drop became high if the thallium pressure was increased sufficiently, Figure 35.

These curves suggest that a certain minimum amount of unalloyed or uncovered free barium is needed at the cathode surface in order to emit a given current or rate of electron flow. The existence of sufficient free barium depends upon the balance between the arrival rate of thallium molecules (which is proportional to vapor pressure) and the diffusion rate of free barium (which is dependent on cathode temperature).

Maximum inverse voltage, as a function of anode temperature, is given in Figure 36 and was obtained in a half-wave rectifier circuit having a series resistance of 25,000 ohms.

A life test was started with the following operating conditions:

1. Cathode heater power, 170 watts (corresponding to a cathode temperature of 1100°C).
2. Wall temperature, 600 to 630°C.
3. Thallium vapor pressure, 8 to 20 microns.
4. Average current, 2 amperes.
5. Peak current, 6 amperes.

Cathode emission was checked during life by measuring the tube drop at various peak currents, yielding the curves shown in Figure 37. The cathode seemed to improve during life, as indicated by the fact that initially the tube drop for 20 amperes (peak) exceeded 25 volts, whereas at the end of the test the tube drop was less than 25 volts for a peak current three times as high.

After 500 hours of operation, the life test was discontinued and the following tests were conducted:

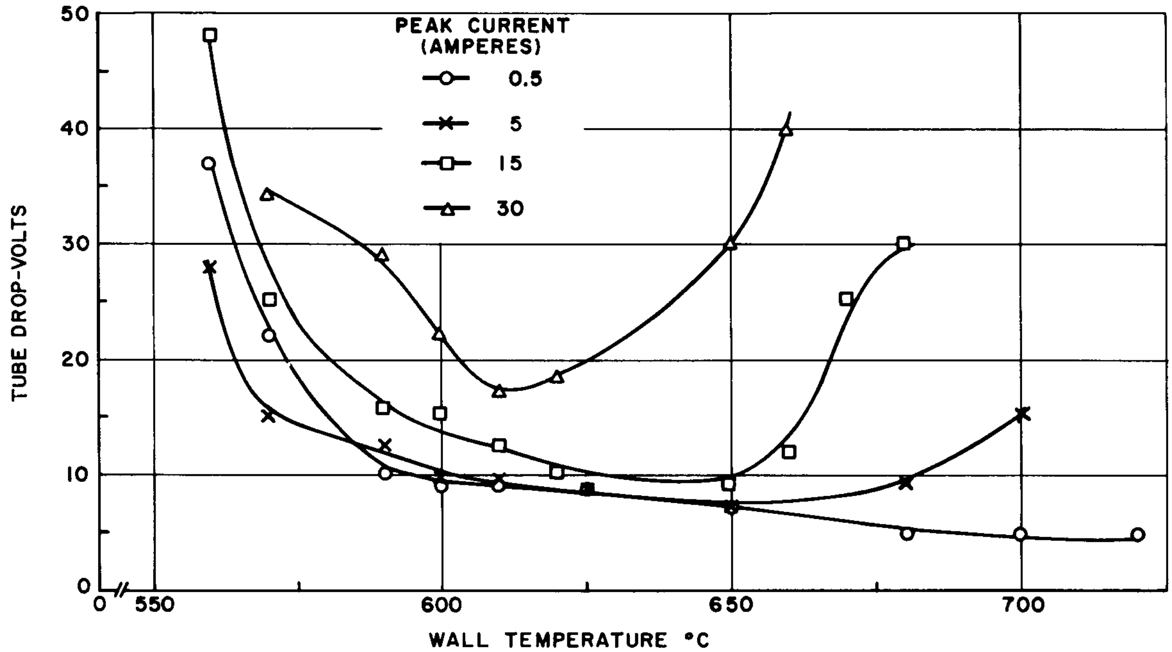

Figure 35 - Tube Drop Versus Wall Temperature, Type Z-7009, Tube No. 19

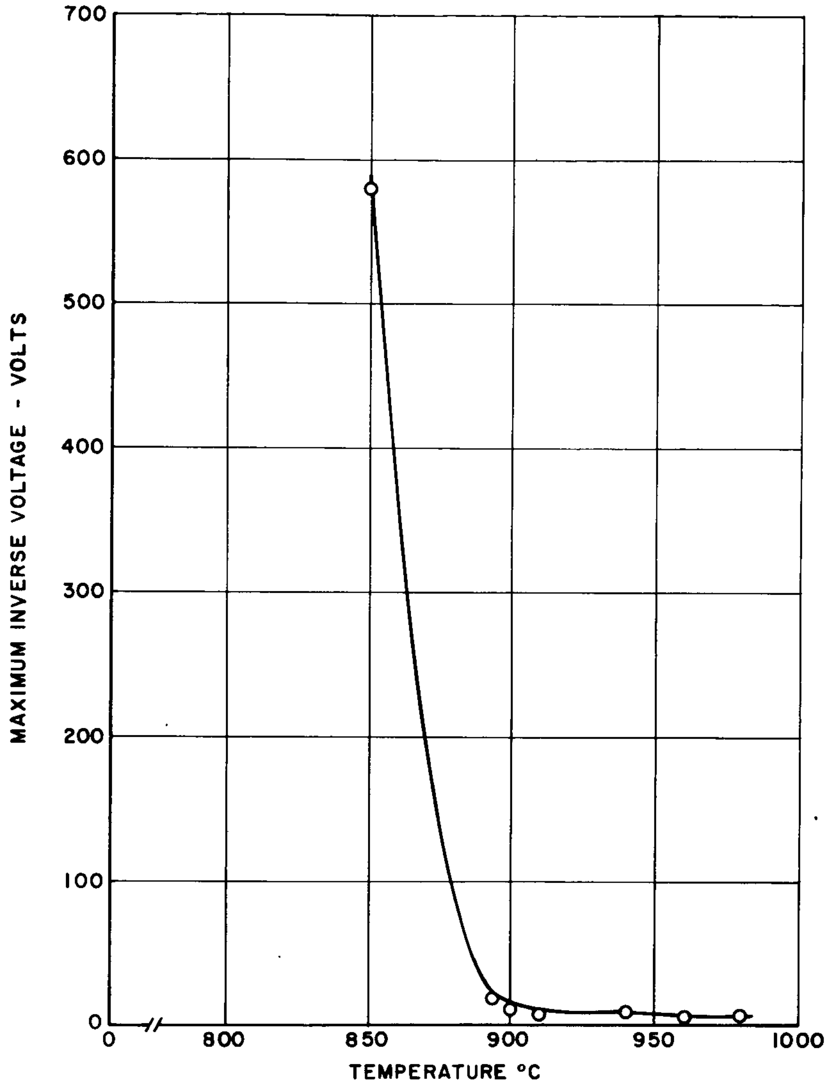

Figure 36 - Maximum Inverse Voltage without Breakdown Versus Anode Temperature, Type Z-7009, Tube No. 19

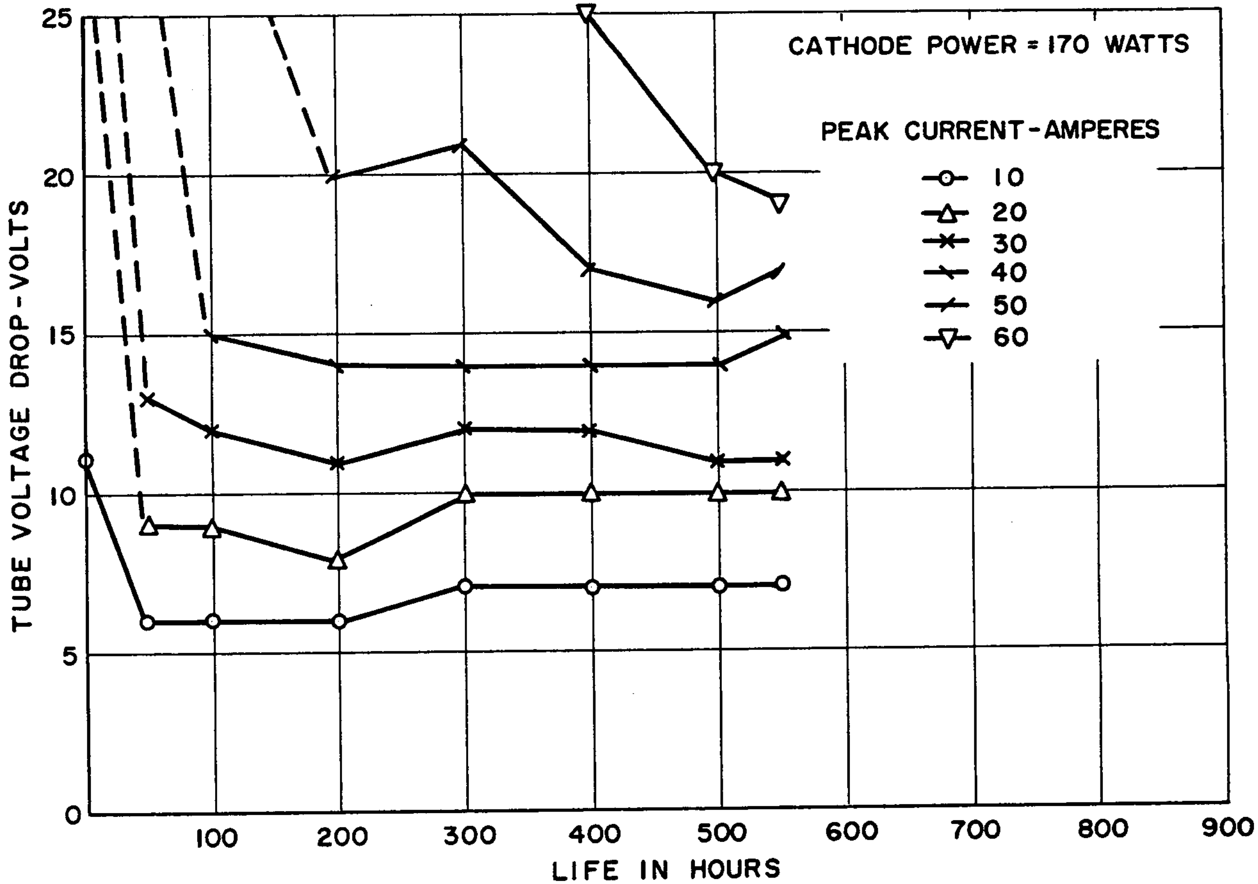

Figure 37 - Tube Drop Versus Life in Hours, Type Z-7009, Tube No. 19

1. Inverse emission versus anode temperature

2. Effect of thallium pressure on cathode emission

3. High-frequency operation

Inverse anode emission had increased so that the maximum anode temperature limit was 800°C, as compared to 850°C initially.

When thallium vapor pressure was increased by elevating the wall temperature to 750°C, cathode emission was reduced, though not to the same extent as indicated by the curves of Figure 35. Emission reduction was temporary as end-of-life emission (Figure 37) was regained, when the tube-wall temperature was reduced.

When connected to a variable-frequency power supply, the tube was successfully operated as a half-wave rectifier at frequencies to 6000 cycles per second. Inverse voltage was set at 150 volts and average current at two amperes. No attempt was made to check the upper limit of thallium pressure during this test. Finally, the tube was operated for two hours at an average current of two amperes, with the supply frequency set at 3000 cycles per second.

REDIRECTION OF CONTRACT

Technical effort to this point indicated that cesium (or cesium compound) is not practical as a fill for a tube that must be operated in a 600°C environment. Excellent emission capabilities were observed in cesium-filled diodes, but the environment must be limited to 300°C because of vapor-pressure considerations and because of a tendency toward inverse and spurious electrode emission at higher temperatures.

Thallium appeared to be a promising fill material for a tube to be used in the 600°C range, but a prepared cathode, which is less efficient than the cesiated type, is required.

The various trade-offs were reviewed by the technical representatives at NASA, and as a result it was recommended that the effort on the balance of the contract be directed toward the development of 15-ampere cesium-filled thyratrons for operation in the 300°C heat-sink range. Three such tubes would be constructed.

CESIUM-FILLED THYRATRONS

Design F, Figure 31 was selected as the starting point for the 15-ampere cesium thyratron. The cathode consists of a spiral-shaped filament similar to the filament proposed for a thoriated-tungsten tube. Because of the higher efficiency of the cesiated cathode, the area was reduced to ten square centimeters, and the operating temperature was reduced from 1600 to about $1000^{\circ}C$. Thus the anticipated input energy to the filament would approximate one volt and 100 amperes.

The scheduling of the three thyratrons was such that the first two tubes were of identical design. The second tube was complete before test information from the first tube was made available. The third tube (Type Z-7009, Tube No. 22) contained a design modification based upon the test results of the first two tubes (Type Z-7009, Tube Nos. 20 and 21).

Peak and average current emission capability is represented in Figures 38 and 39. The selection of a filament voltage input of one volt is reasonable, as Figure 40 indicates that it is 0.2 volt higher than the voltage at which tube drop rapidly increases, yet no gain is realized by increasing the voltage higher than one volt.

Anode dissipation was investigated from two standpoints. The maximum temperature to which it could be operated without arc-back, and whether proposed heat-sink connections appeared adequate for holding anode temperature below the critical value at full average current conduction, was of interest. These thyratrons were constructed (Figure 31) such that the thermal path for carrying away anode dissipation consisted of:

1. A molybdenum block about one-inch diameter by one-inch long, extending from the inner anode surface to the top of the tube.

2. A four-inch diameter, 1/4-inch thick, copper disc.

3. Two additional copper discs for bridging the gap between the four-inch disc (item 2) and the heat sink. In an actual application, these two discs could be bolted together with a thin mica insert between them, the insert providing the necessary insulation between heat-sink and anode potentials. The diameter of the above discs were 6-1/2 and 8-1/2 inches, respectively.

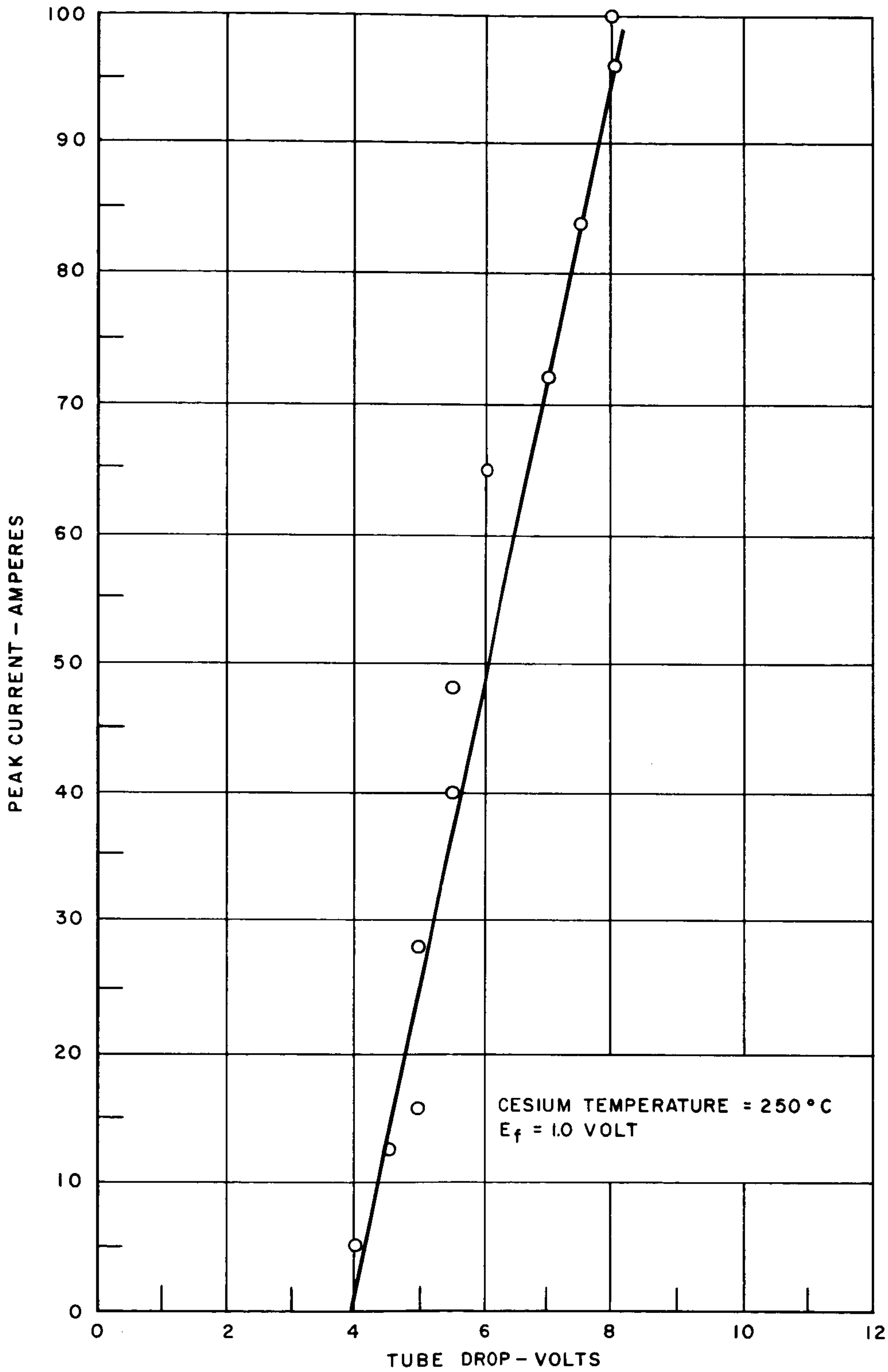

Figure 38 - Current Versus Voltage, Type Z-7009, Tube No. 22

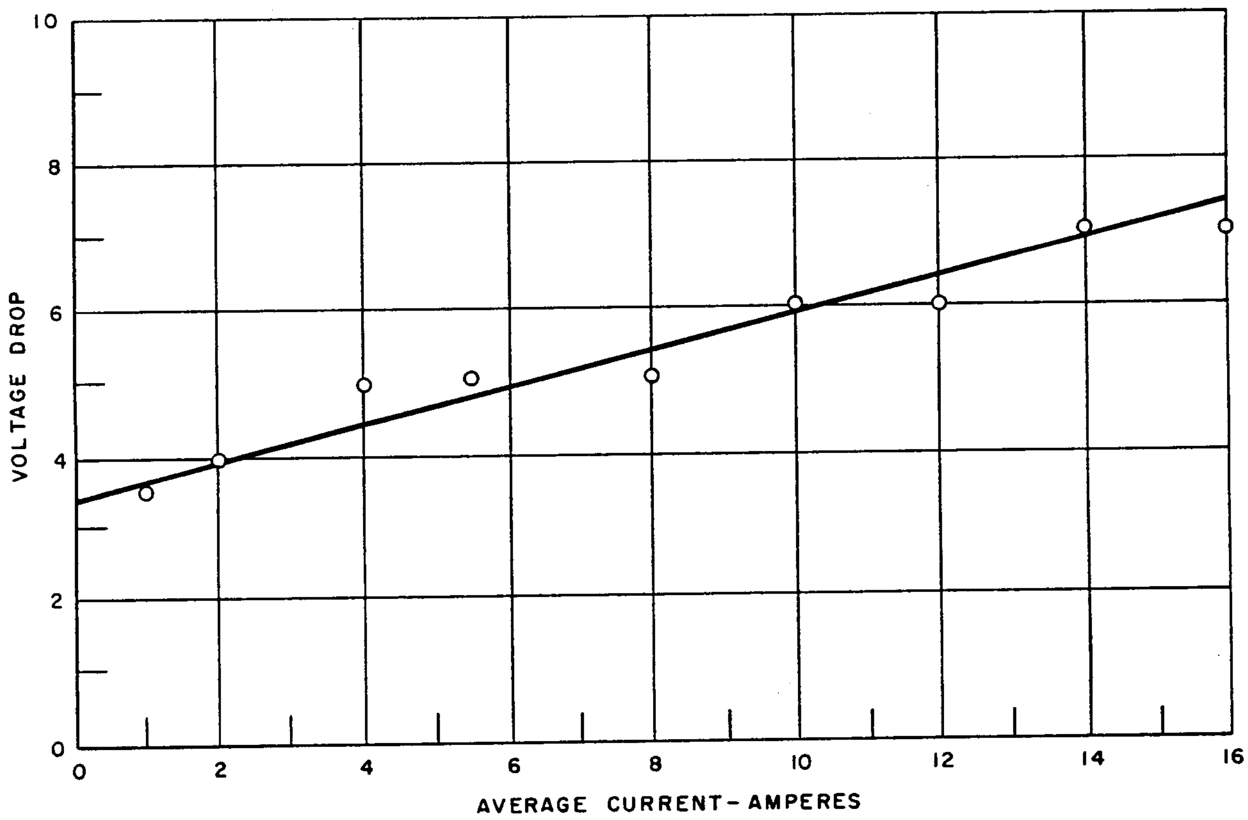

Figure 39 - Voltage Drop Versus Average Current, Type Z-7009, Tube No. 22

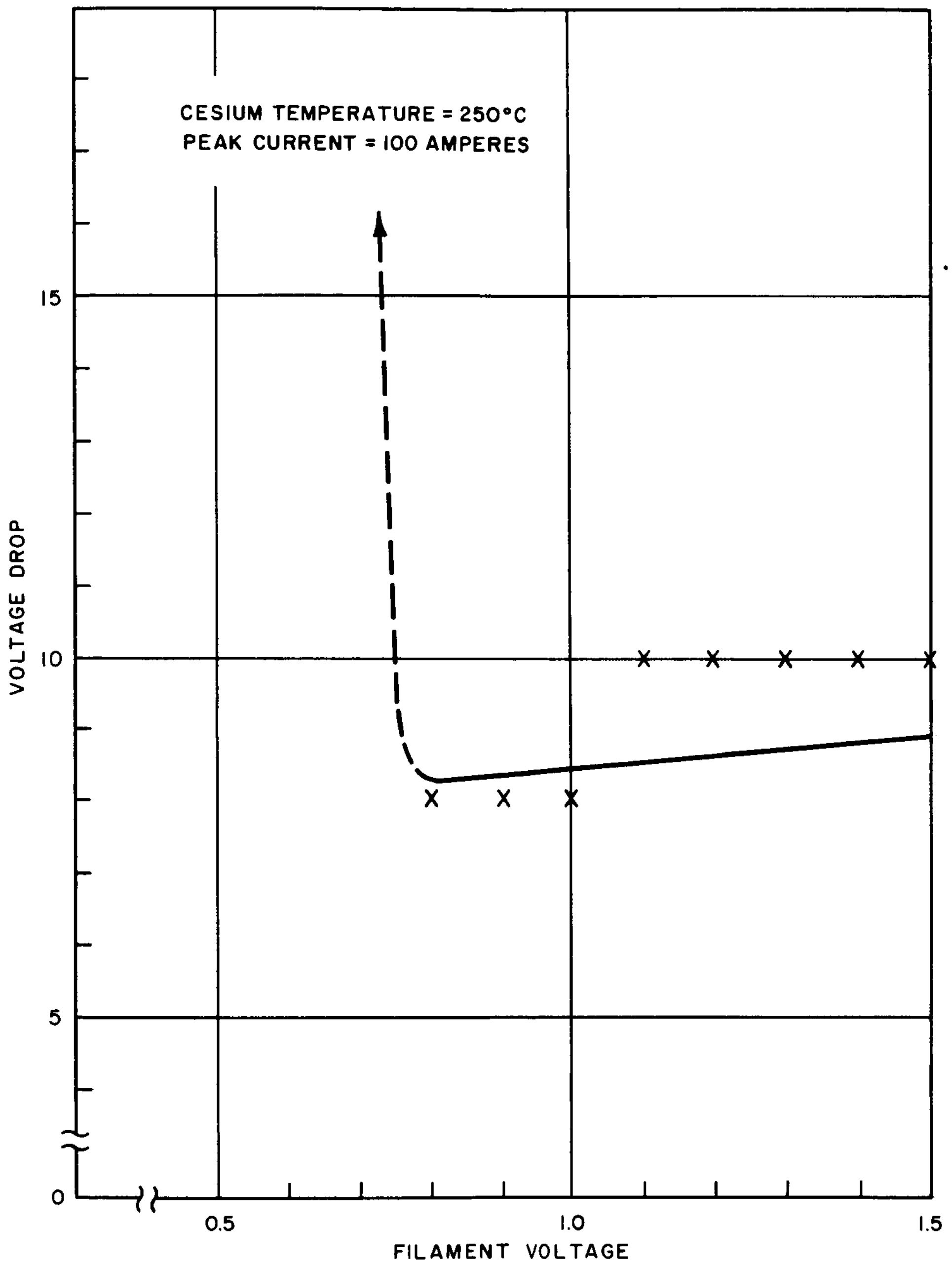

Figure 40 - Voltage Drop Versus Filament Voltage, Type Z-7009, Tube No. 22

In lieu of actually operating the tubes inside of a 300°C chamber, anode dissipation was studied using a synthetic approach. With heat-sink connecting elements bolted to the tube, the tube was operated at full-rated average current. Additional power was injected into the anode system by means of an external heater to provide a means of raising the temperature of the anode system further. With the edge of the anode system (or the part that would be bolted to a heat sink) at 300°C, it was determined that the tube was free from arc-back at 150 volts inverse.

From another measurement, with no copper discs connected to the molybdenum anode, it was shown that the tube would arc back at 150 volts inverse if the anode surface temperature reached 410°C. By raising the temperature of the full anode system until arc-back occurred, a crude estimate of the temperature drop between anode and heat sink could be made. This would be equal to the difference between 410°C (the internal arc-back temperature) and the temperature at the outer edge of the anode system. Pursuing this course, an arc-back occurred when the edge of the anode system reached 380°C, yielding an apparent Δt of 30 degrees. There is reason for assuming that if the tube were contained within an actual 300-degree heat sink, this Δt would be doubled, or approximately 60 degrees. The reason for this is that in an actual heat sink, all of the Q from the anode would be conducted through the linkage to the heat sink. In the synthetic test described, the average Q traversing the full extent of the heat linkage is closer to one half of the Q entering the linkage, since all heat is lost by radiation from the anode system rather than conducted in full to a heat sink. Thus, the tube would appear capable of operating to 150 volts inverse, with a heat-sink temperature of 410 - 60 (arc-back temperature less $2\Delta t$) = 350°C. From the curves of Figure 27 it would appear that an additional temperature reduction of 50 degrees is required to raise the critical anode voltage at which arc-back occurs from 150 to 750. Thus it appears that the tube is marginally capable of reaching 750 volts inverse, with a 300 degree heat sink.

By varying the number of heat-linkage discs, the anode could be provided with a radiator of 1, 4, 6-1/2 or 8-1/2 inches diameter. Figure 41 demonstrates the relation between anode system temperature and average current for these various-size radiating surfaces. The curves extend to an average current of 15 amperes, or to the point where an arc-back was observed (inverse voltage = 150). A plot of grid temperature is given in Figure 42.

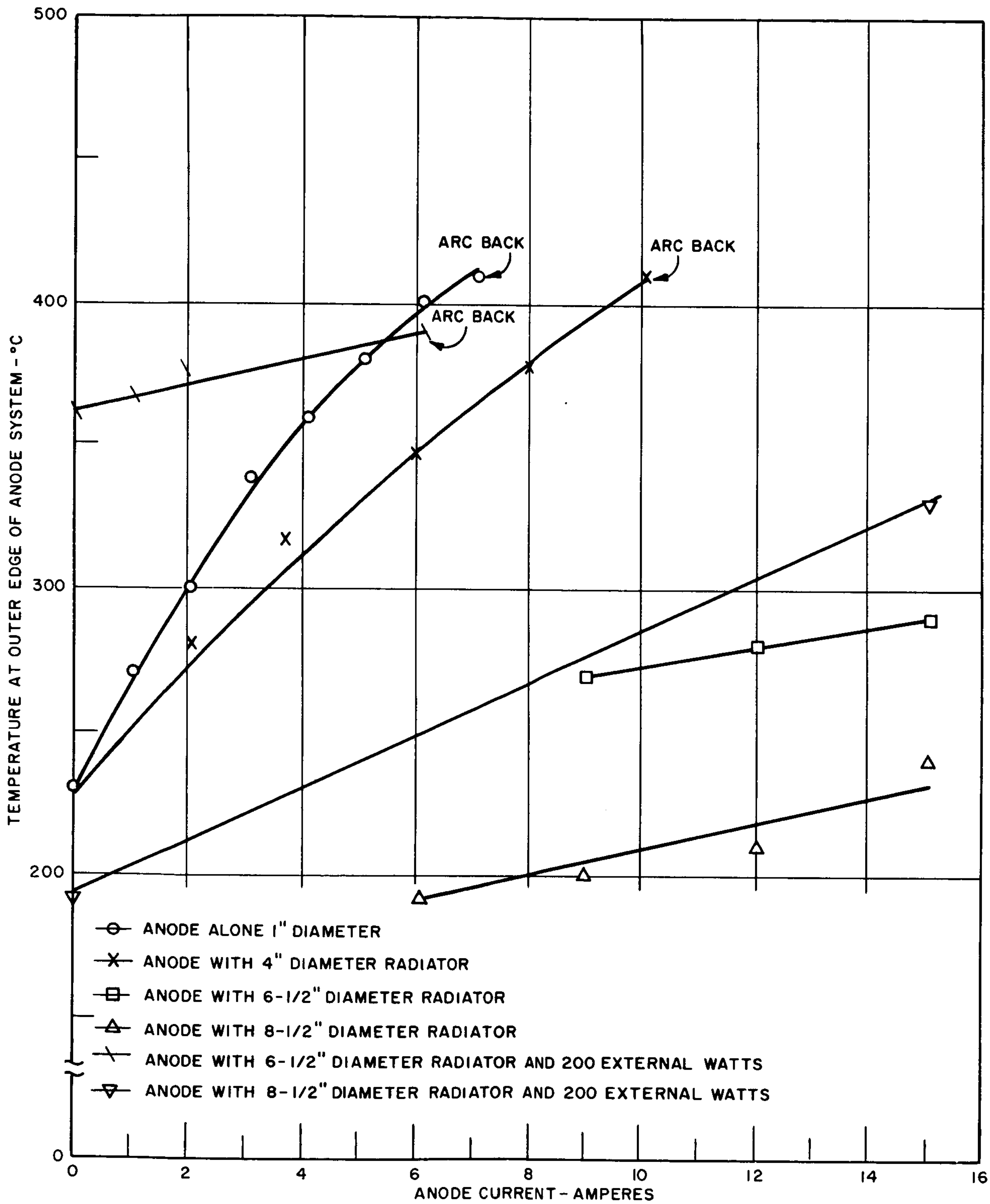

Figure 41 - Anode Temperature Versus Average Current, Type Z-7009, Tube No. 20

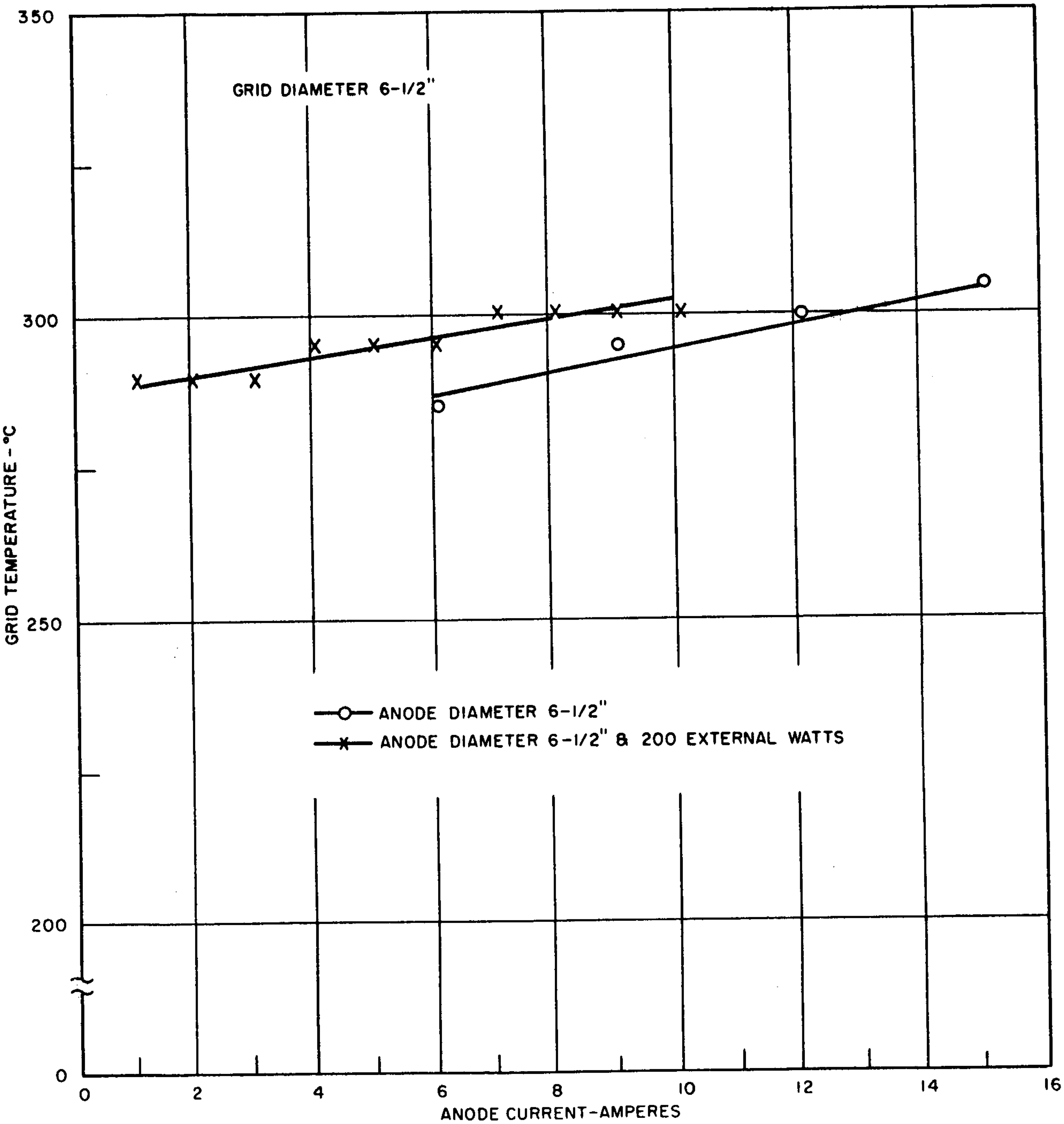

Figure 42 - Grid Temperature Versus Average Current, Type Z-7009, Tube No. 20

Figure 43 presents the D-C grid control characteristic. The curve flattens at an anode voltage of 300 volts. This represents the maximum voltage that may be impressed between anode and grid. Further increase in negative bias will in fact reduce the anode voltage at which breakdown occurs; that is, if the control grid is driven to -100 volts, the maximum anode voltage becomes 200 volts. The breakdown voltage of a gap is dependent upon the product of electrode separation and gas or vapor pressure (Paschen's Law). Hence, the maximum forward and inverse voltages, as a function of cesium temperature, are seen to vary as shown in Figure 44 and as a function of cesium pressure, Figure 45. The curve of breakdown voltage appears to reach a minimum at about 400 volts for a cesium pressure of two millimeters. We know of no published Paschen's curve for cesium for comparison, but since most gases exhibit a minimum breakdown voltage in the general range of five for the product of PD (where P is pressure in millimeters of mercury and D is gap length or electrode separation in millimeters), it is of interest to compare the cesium data to published data for air.[2] For this comparison the inverse voltage curve, Figure 45, was used with the grid anode spacing of 1/8 inch = three millimeters, Figure 46. The forward voltage curve, Figures 44 and 45, is displaced lower than the inverse voltage curve for two reasons:

1. The effective spacing for the grid-anode gap for the forward-voltage case is greater than the actual electrode spacing because of the openings in the grid.

2. In the forward-voltage case, electrons emitted by the hot cathode are available for precipitating a discharge. For the inverse case, the electrons must emanate from the relatively cold anode.

Based upon the above data, two alternatives are open for achieving the objective rating of 750 volts inverse.

1. Reduce the controlling temperature for the cesium below 300°C.

2. Resort to the use of gradient grids.

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2. James D. Cobine, Gaseous Conductors, 1st Edition, p. 164, McGraw-Hill Co., New York, 1941.

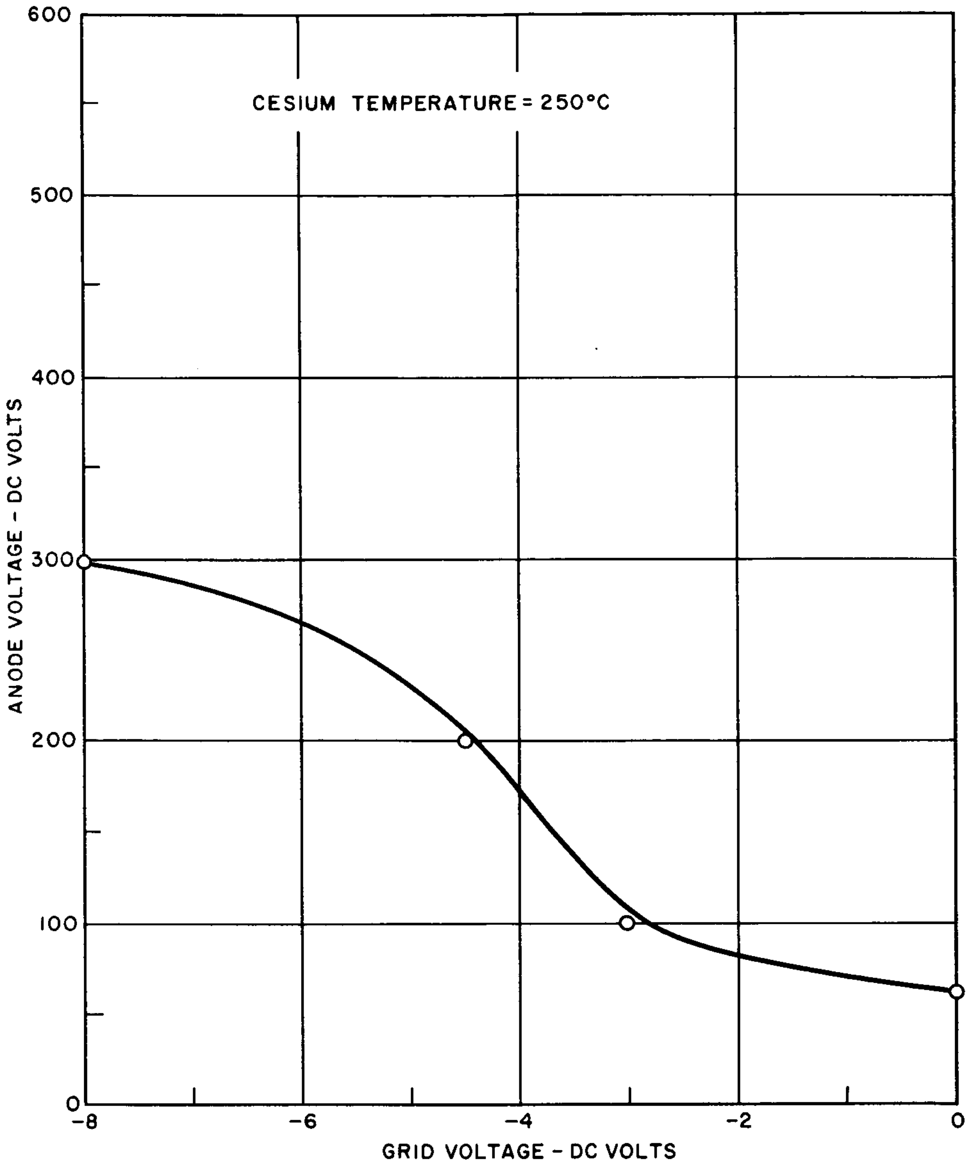

Figure 43 - D-C Control Grid Characteristic, Type Z-7009, Tube No. 21

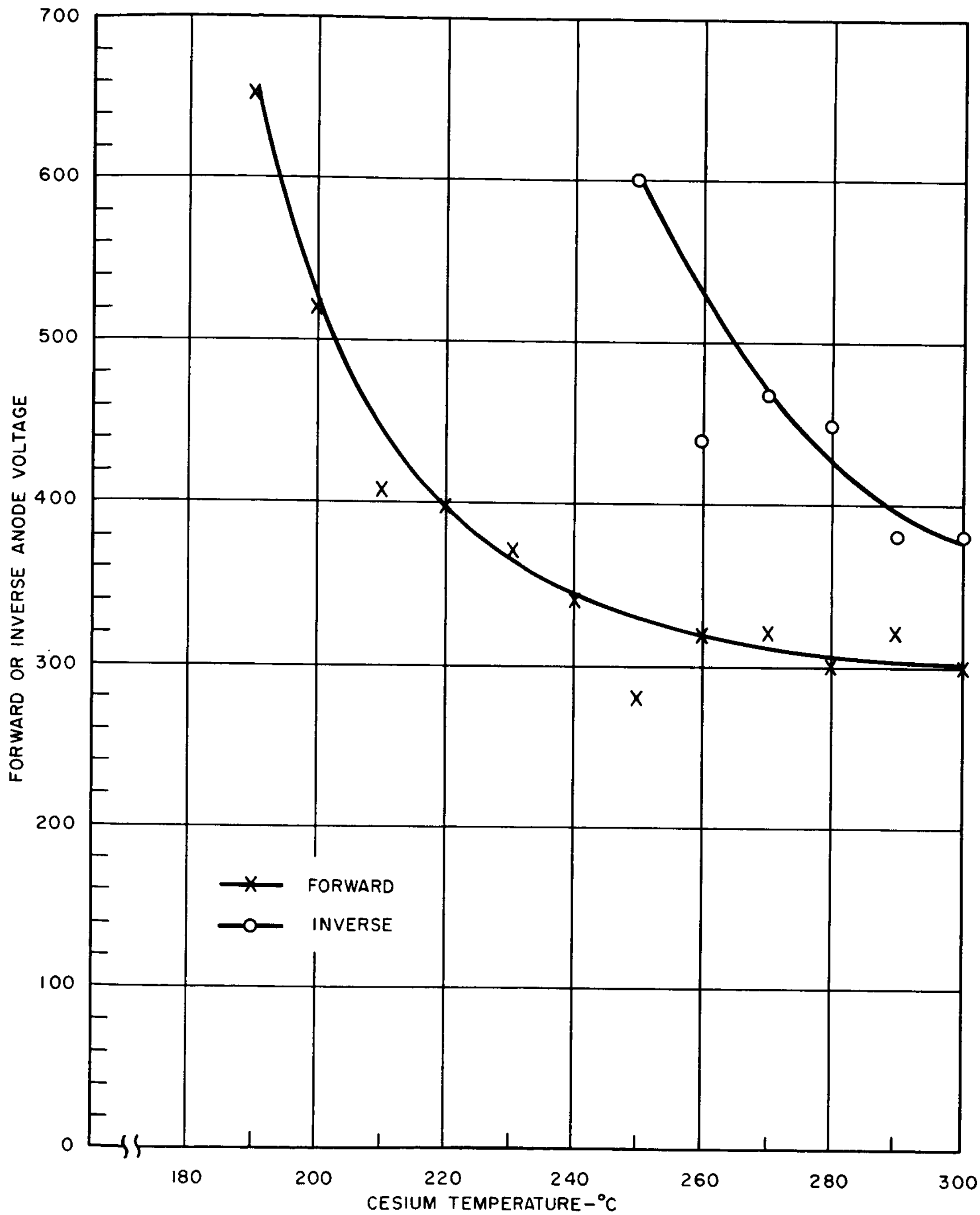

Figure 44 - Maximum Anode Voltage Versus Cesium Temperature, Type Z-7009, Tube No. 21

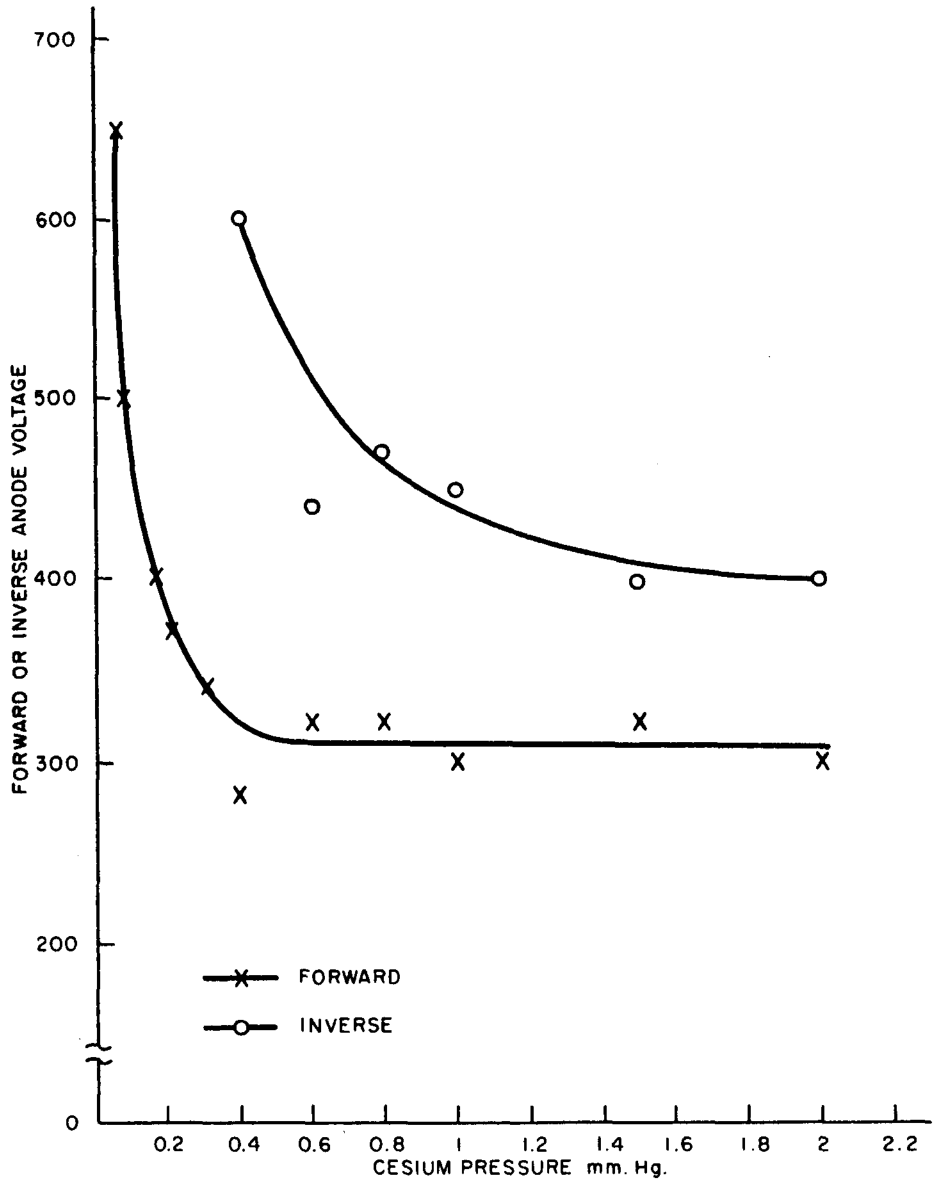

Figure 45 - Maximum Anode Voltage Versus Cesium Vapor Pressure, Type Z-7009, Tube No. 21

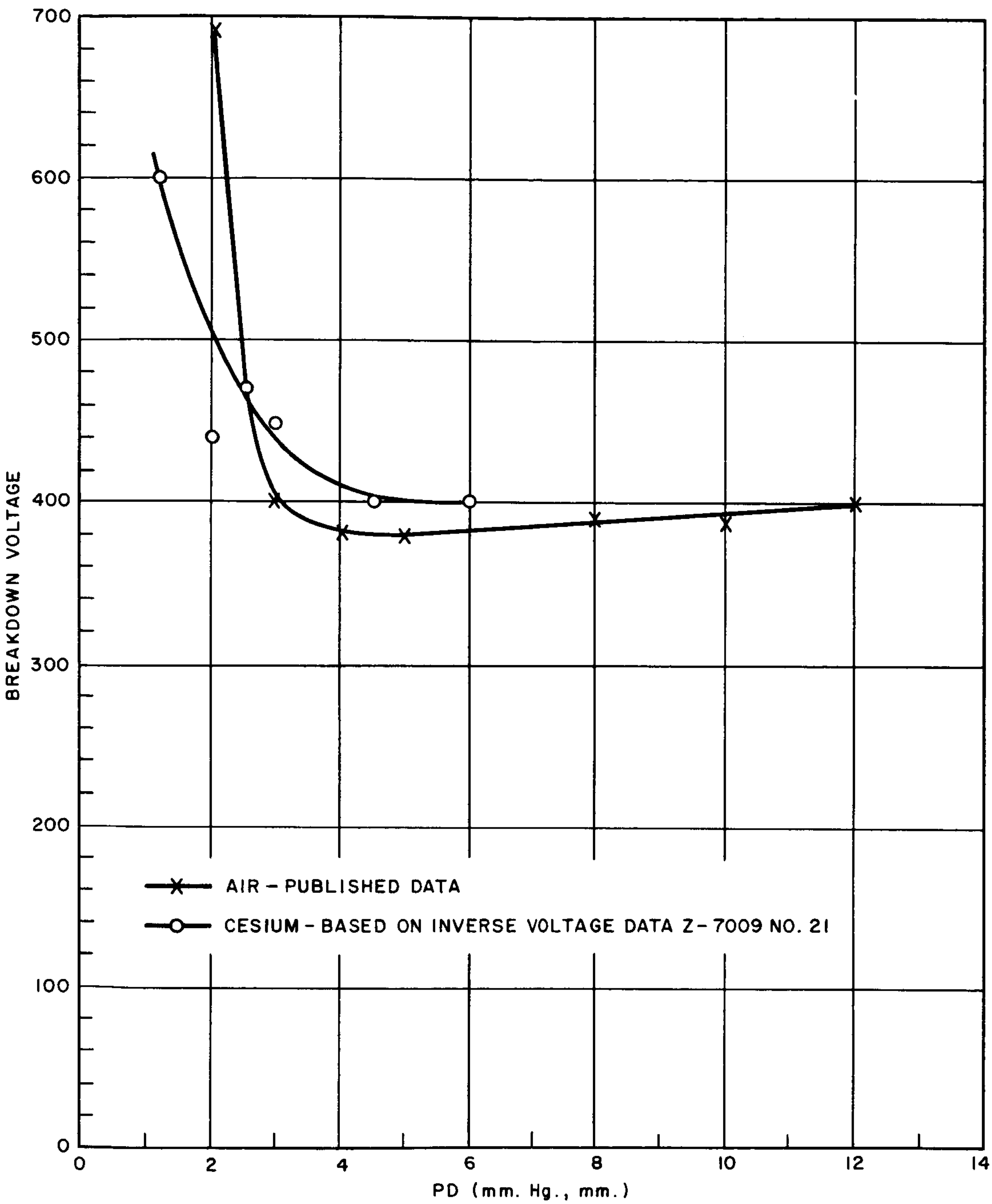

Figure 46 - Breakdown Voltage for Air and Cesium Versus PD

Operation at 750 volts in a simple triode structure may be possible if the cesium reservoir temperature is held to a maximum of 230°C. Under these conditions, the grid and anode could still reject heat to a 300-degree heat sink because the cesium vapor pressure would be governed by the coolest spot in the tube.

Full-voltage operation at 300 degrees might be achieved by adding two gradient grids between anode and control grid. Such an approach would provide three gaps in series to divide the inverse voltage. One gradient grid would be inadequate because experience with other thyratrons has shown that the addition of a gradient grid increases the voltage capability only about 50 percent above the capability of the triode.

Two grid control problems were evident with respect to both Tube Nos. 20 and 21. A low leakage resistance between grid and anode, presumably created by the formation of a cesium film on the ceramic insulator, required an increase in bias and driving power. Grid emission occurred above a certain critical temperature and caused complete loss of control. These problems are described separately.

One of the desirable characteristics of a typical thyratron is its ability to control large quantities of power flow with a very small power input to the grid. Thus it is commonplace for a thyratron grid to be energized from a high-impedance circuit, as high as 10 megohms for some industrial applications. The grid-anode leakage resistance should be many times higher than the resistance of the grid driver circuit. If this is not the case, an excessive bias supply voltage must be provided to compensate for the portion of anode voltage that is coupled to the grid as a result of internal leakage. The excess bias supply voltage requirement is approximately equal to the ratio of $R_g/R_{ga}(V_a)$ where:

R_g is the resistance of the grid circuit in ohms, and
R_{ga} is the grid-anode leakage in ohms.

The general case has been derived for predicting the grid bias supply voltage required to prevent conduction in a thyratron, as follows:

$$V_b = V_a + V_a \left(\frac{R_{ga} + R_g}{R_{ga} + R_{gc}}\right) - \left(V_a + V_g\right)\left(\frac{R_{ga} + R_g}{R_{ga}}\right),$$

where:

V_b = bias supply voltage

V_a = peak anode voltage

V_g = critical grid voltage corresponding to V_a and obtained from D-C control-grid characteristic

R_{ga} = grid anode leakage resistance

R_{gc} = grid cathode leakage resistance

R_g = internal resistance of grid driving circuit

Leakage paths measuring from one ohm to one megohm were observed, the magnitude of the leakage depending upon ceramic and electrode temperatures and previous history of operation. Figure 47 presents a comparison of actual and theoretical excess or overvoltage required at the grid supply. When the leakage equals the grid circuit resistance, as many bias supply volts are required as there are anode volts to be held off.

Heat was supplied to the grid-anode ceramic in an attempt to reduce the arrival rate of cesium molecules. With a one-turn heater looped around the midpoint of the ceramic, the leakage resistance could be studied as heater power input was varied. Because of the random nature of the cesium-film deposition, the results were not perfectly repeatable. However, a typical account of the leakage resistance, as a function of heater input voltage and average current, is given in Figure 48. In this figure, the abscissa changes were made at five-minute intervals. With the application of external heat, the leakage path could be controlled so that the grid-anode impedance minimum was typically 10,000 ohms. By increasing the amount of heating, the minimum impedance could be raised. It appears that any final-design cesium thyratron should have a heating circuit directly attached to the grid-anode ceramic. One way of fulfilling this requirement may be to print the heating circuit onto the ceramic by metallizing.

Tube Nos. 20 and 21 exhibited grid control only if the average current were low and the temperature at the edge of the grid was below 300°C, Figure 49. The thermal problem was emphasized by the fact that higher average currents could be controlled for the time required to raise the temperature at the center of the grid to the critical emitting temperature. At 16 amperes this time was only about two seconds, Figure 50.

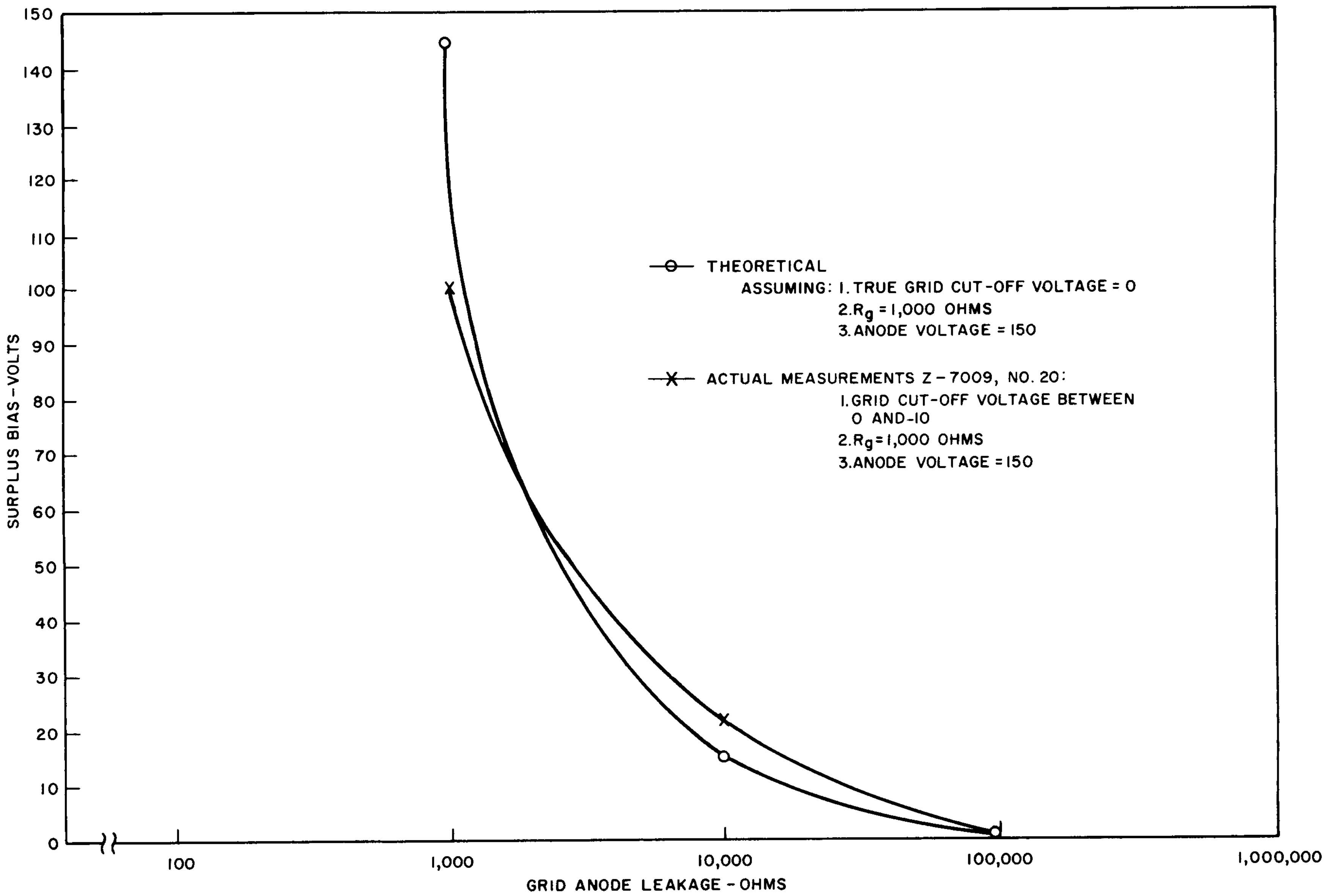

Figure 47 - Surplus Bias Supply Voltage Needed to Compensate for Grid Anode Leakage

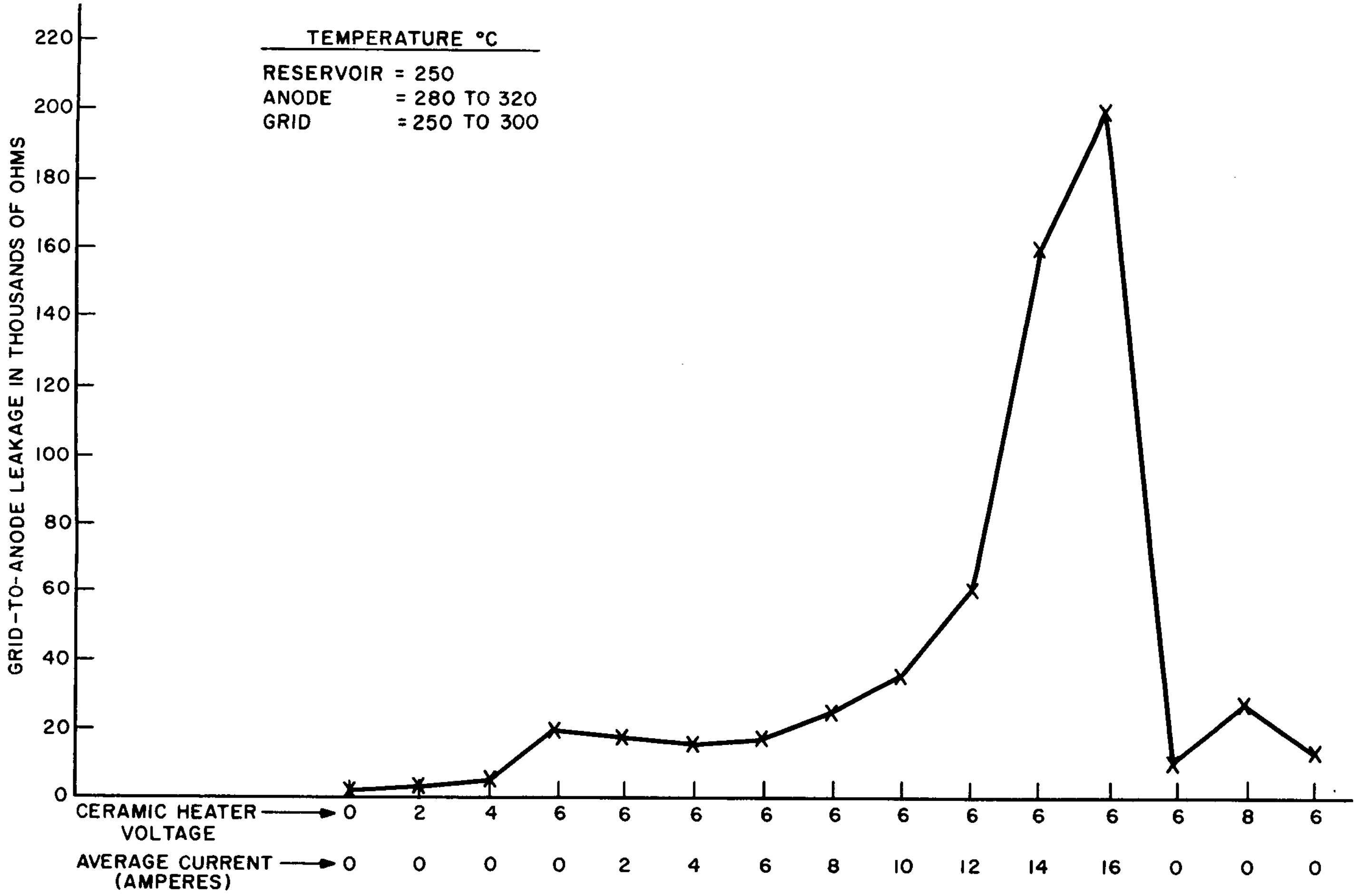

Figure 48 - Grid-to-Anode Leakage Versus Ceramic Heater Voltage and Average Current, Type Z-7009, Tube No. 21

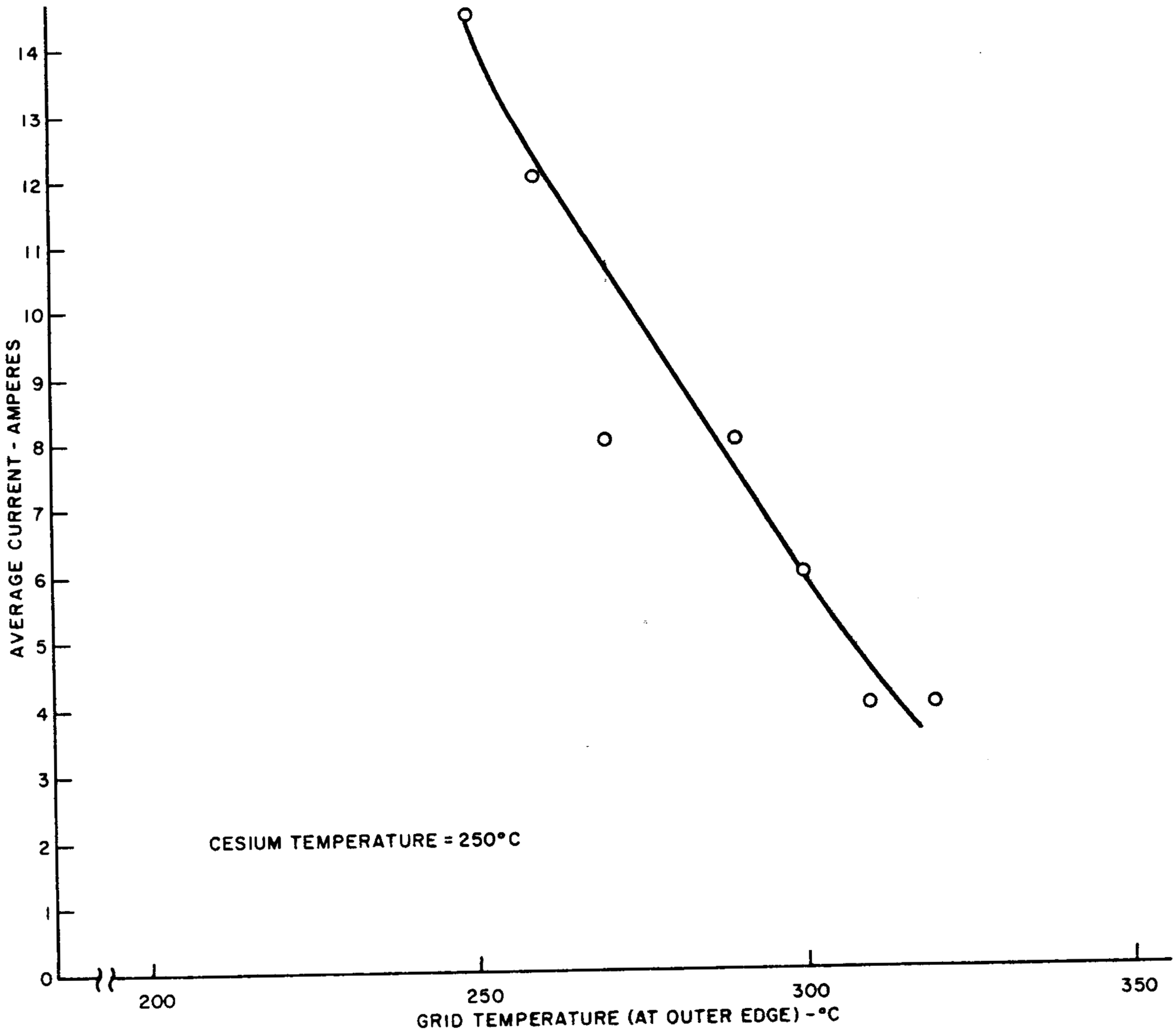

Figure 49 - Maximum Average Current with Grid Control Versus Grid Temperature, Type Z-7009, Tube No. 21

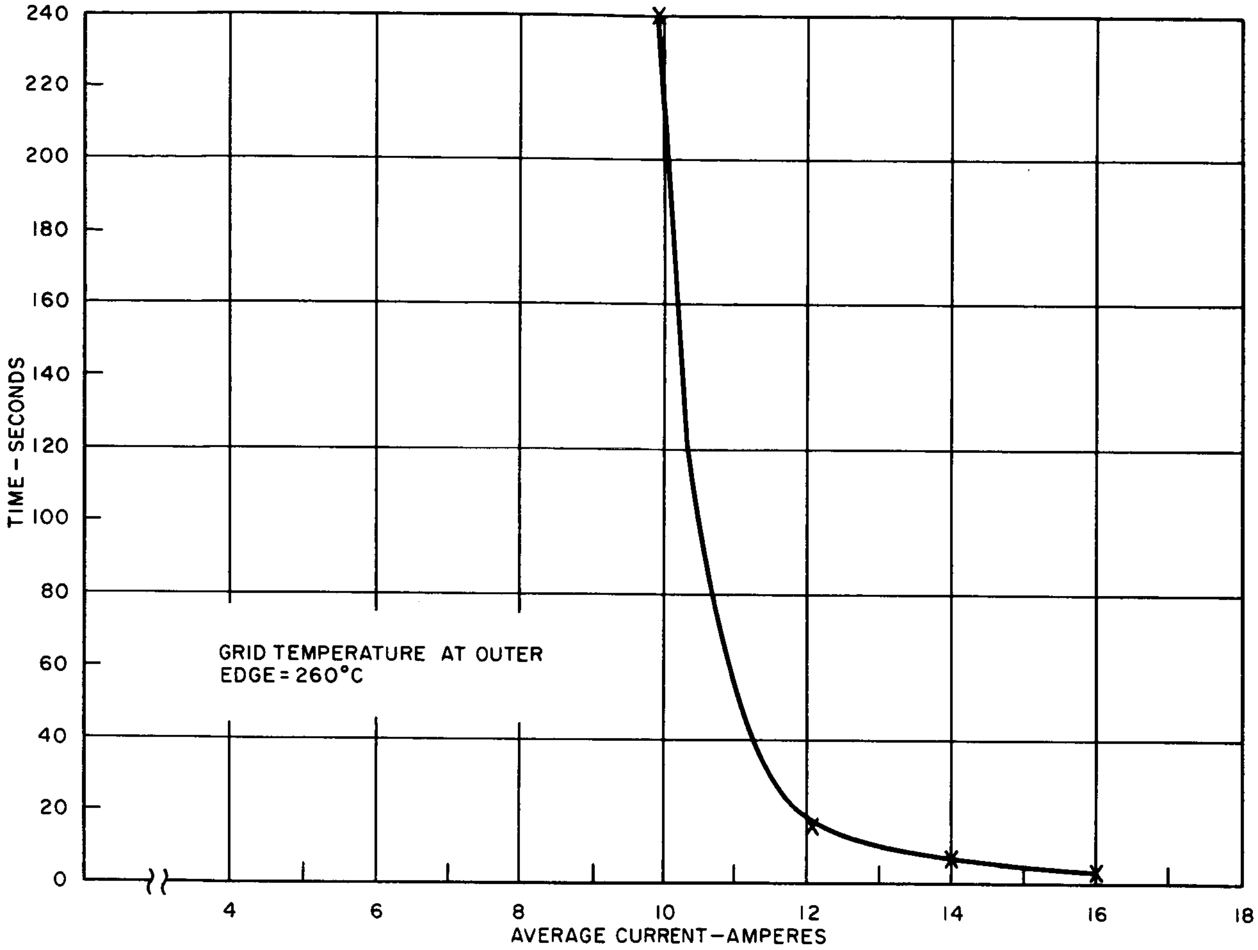

Figure 50 - Maximum Operating Time with Grid Control Versus Average Current, Type Z-7009, Tube No. 21

The grids of Tube Nos. 20 and 21 were from 1/8-inch iron and slotted in such a way as to leave 1/16-inch wide bars, Figure 51, at the center. These bars were the most vulnerable part of the grid, with respect to a significant temperature gradient. A temperature gradient was calculated based upon the following assumptions.

1. Anode dissipation is 100 to 150 watts.

2. About ten percent of the above or ten watts, dissipation appears at the grid because of the discharge going through the grid.

3. All of the discharge might concentrate at one slot, thus causing the dissipated energy to divide equally between the two boundary bars for the particular slot.

4. The dissipated energy for each bar enters the bar as a point source at the center of the bar, and one-half of the entering energy flows out of each end of the bar.

5. The longest bar is considered in order to develop the worst case of temperature rise.

Thus:

$$T = \frac{PL}{KA} = \frac{2.5\ (0.95)}{0.67\ (0.05)} = \frac{2.4}{0.033} = 72^{\circ}C,$$

where:

T = temperature rise in degrees centigrade between end of bar and its midpoint

P = one-half the power entering the grid bar

$$= \frac{5}{2} = 2.5 \text{ watts}$$

L = one-half the length of the longest bar

$$= 3/8 \text{ inches} = 0.95 \text{ centimeters}$$

K = coefficient of thermal conductivity for iron = $0.67 \dfrac{\text{watts}}{(\text{cm})\ (^{\circ}\text{C})}$

A = cross section area of

$$\text{bar} = (1/16)(1/8)\ \frac{1}{128}$$

$$= 0.0078 \text{ square inches}$$

$$= 0.05 \text{ square centimeters}$$

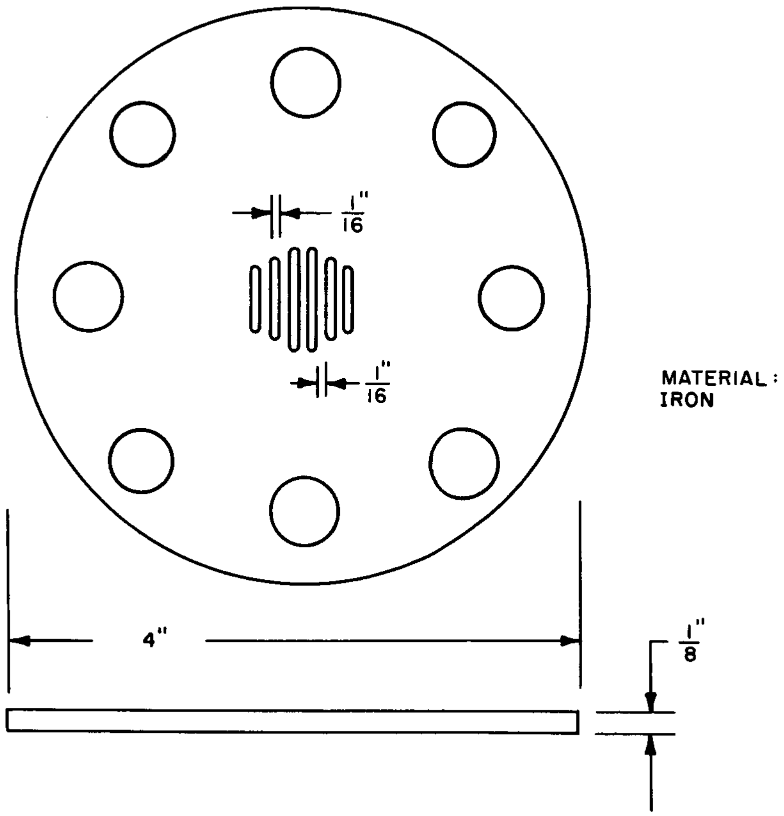

Figure 51 - Control Grid Design for Type Z-7009,
Tube Nos. 20 and 21

With the aforementioned assumptions, the center of the bar could run 72°C hotter than the ends of the bar. This temperature rise should be added to the temperature rise occurring between the outer edge and the portion of the grid containing the slots. To calculate the latter temperature rise, the following procedure was used:

1. $$Q = \frac{t_i - t_o}{(1/2\pi KL) \ln \frac{r_o}{r_i}}$$

   is given for the case of radial heat conduction in a tube having an inner radius r_i, and outer radius r_o, and a length L.[3]

2. The above formula may be converted to

   $$P = \frac{T}{\left[(1/2\pi K\ th) \ln \frac{r_o}{r_i}\right]}$$

   for which

   $$T = \frac{P}{2\pi K\ th} \ln \frac{r_o}{r_i}$$

3. Heat flows from the innermost part of the grid radially to the outer edge. The innermost part of the grid is considered as a circular opening which will barely contain the slotted portion of the grid. For the grids discussed the circular opening has a diameter of 3/4 inch.

4. The amount of heat flow is equal to the power arriving at the grid from the cathode plus the grid dissipation in consequence to the discharge. This is the aforementioned 10 watts plus 1/2 cathode power = 10 + 40 = 50 watts.

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3. E. R. G. Eckert, Robert M. Drake, Jr., Heat and Mass Transfer, 1st Edition, p. 37, McGraw-Hill Co., New York, 1959.

5. The values are now known for calculating T, the temperature rise.

$$P = 50 \text{ watts}$$

$$K = 0.67 \frac{\text{watts}}{(\text{cm})(^{\circ}\text{C})}$$

$$th = \text{thickness of grid} = 1/8 \text{ inch} = 0.32 \text{ cm}$$

$$= \text{outer radius of disc} = 2 \text{ inches} = 5.08 \text{ cm}$$

$$= \text{inner radius of disc} = 3/8 \text{ inch} = 0.95 \text{ cm}$$

Thus:
$$T = \frac{50}{2\pi\ (0.67)\ 0.32} \ln \frac{5.08}{0.95}$$

$$= \frac{50}{1.34} \ln 5.3$$

$$= 37.4\ (1.67) = 62^{\circ}\text{C}.$$

The total temperature rise from the outer edge to the center of the grid = 72 + 62 = 134°C.

Three modifications were made in a redesign of the grid (Figure 52) for Type Z-7009, Tube No. 22, to reduce the temperature gradient at the grid.

1. The material was changed from iron to copper. With the higher conductivity of copper, K = 3.88, a gain of 3.88/0.67 = 5.8 should be realized.

2. The thickness of the grid was changed from 1/8 to 1/4 inch, causing another gain of 2.

3. In addition the width of the grid bars was changed from 1/16 to 3/32 inch, producing another gain of 1.5 at the grid bars.

The over-all gain (or reduction factor for temperature gradient) at the grid bars becomes 5.8 (2)(1.5) = 18, and the over-all gain for the solid outer portion of the grid becomes 5.8 (2) = 11. For the proposed copper grid, and the same power assumptions made for the iron grid, the temperature rise at the grid bar = 72/18 = 4 degrees and for the outer portion = 62/11 ≅ 6 degrees. Thus, the hot-spot temperature of the copper grid should be only about ten degrees centigrade higher than the temperature at the outer edge.

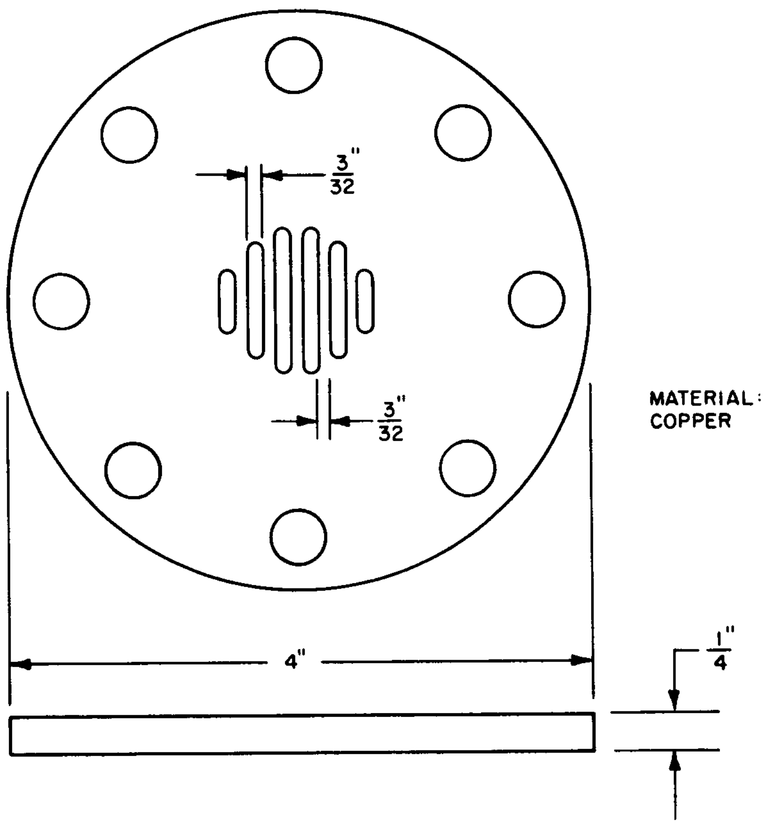

Figure 52 - Control Grid Design for Type Z-7009,
Tube No. 22

Test results for Type Z-7009, Tube No. 22, confirmed the above estimates, and grid control at 15 amperes average was demonstrated for temperatures (measured at the outer edge of the grid) to 360°C maximum, or roughly 100 degrees higher than the corresponsing maximum temperature for the iron grid. Figure 53 illustrates the comparison as a function of average current. With these measurements and the knowledge of the relative conductivities of the grids, it may be estimated that the critical hot-spot temperature at which grid control is lost is about 375°C. While Tubes Nos. 21 and 22 were compared initially under similar conditions and with reservoir temperatures of about 250°C, subsequent testing of No. 22 over a long period of time and with other reservoir temperatures indicated that grid temperature should be limited to 300°C maximum. This point will be discussed further in the "Endurance Run" section which follows.

The grid characteristic and maximum controllable voltage for Tube No. 22 are given in Figures 54 and 55, respectively.

High-frequency performance was appraised by connecting the tube and load to a variable-frequency power supply and determining at what frequency grid control deteriorated. Anode voltage was set at 110 volts R.M.S., since with available equipment it was impossible to have high voltage and high current simultaneously.

It was determined that up to a certain frequency, grid control was not altered from the 60-cycle case. Above this frequency there was a rapid rise in the negative grid-supply voltage needed to maintain grid control. This reflected the need, at high frequency, of collecting ions at the grid or permitting the grid to contribute to the deionization of the tube. The increase in grid-supply voltage over that needed for the 60-cycle case was termed excess bias supply voltage, and the latter was plotted as a function of frequency, Figure 56, for various average currents. The effect of cesium temperature on high-frequency performance is given in Figure 57. In the above testing, a full half-cycle was available for deionization and recovery. The maximum frequency attainable by cesium tubes in an inverter circuit would be considerably reduced, since in such a circuit only a fraction of the half-cycle is available for recovery.

ENDURANCE RUN

The purpose of the endurance run was to subject one of the Type Z-7009 thyratrons to a 1000-hour test at rated load and voltage while operating at an environmental temperature of 300°C.

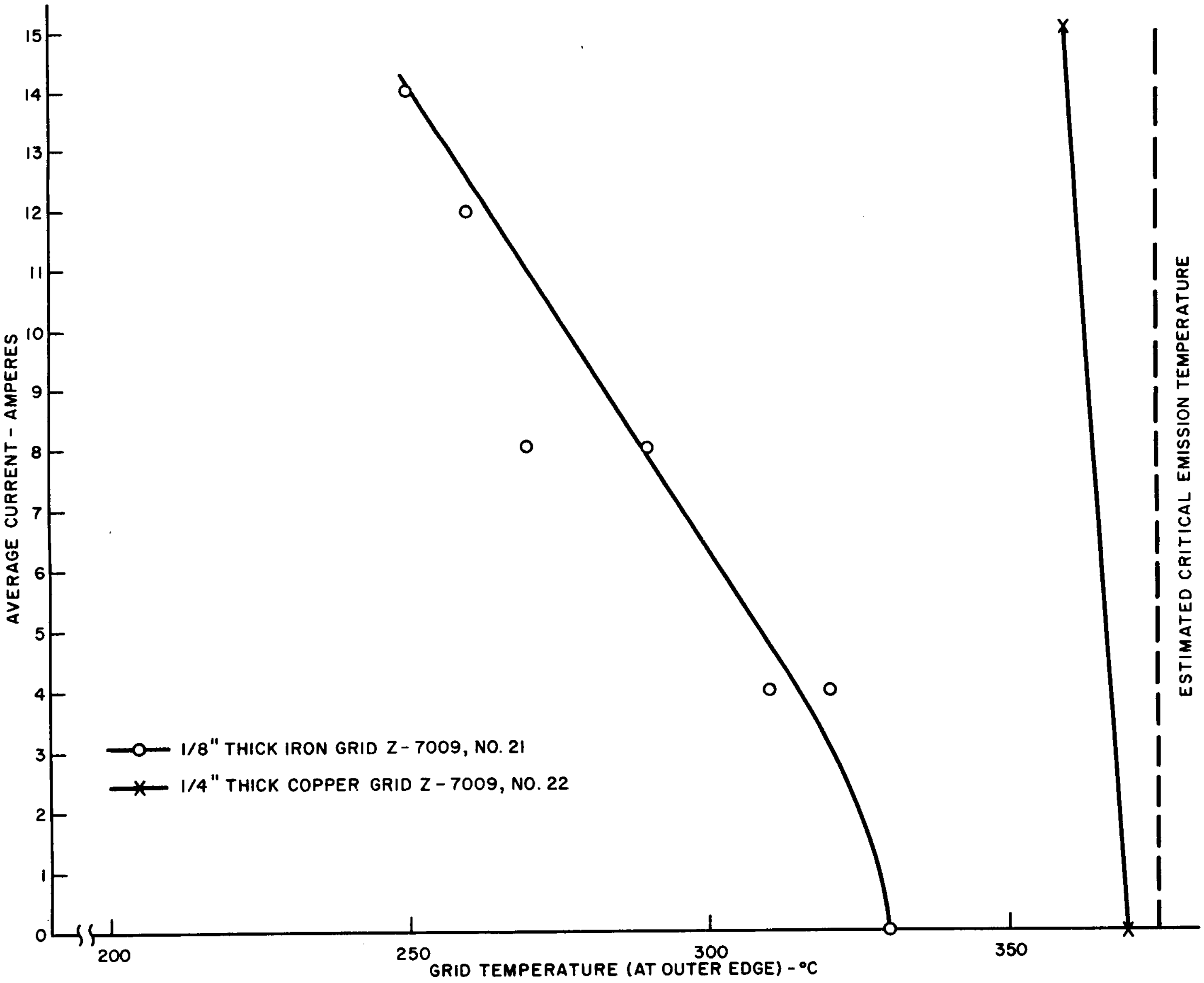

Figure 53 - Maximum Average Current with Grid Control Versus Grid Temperature

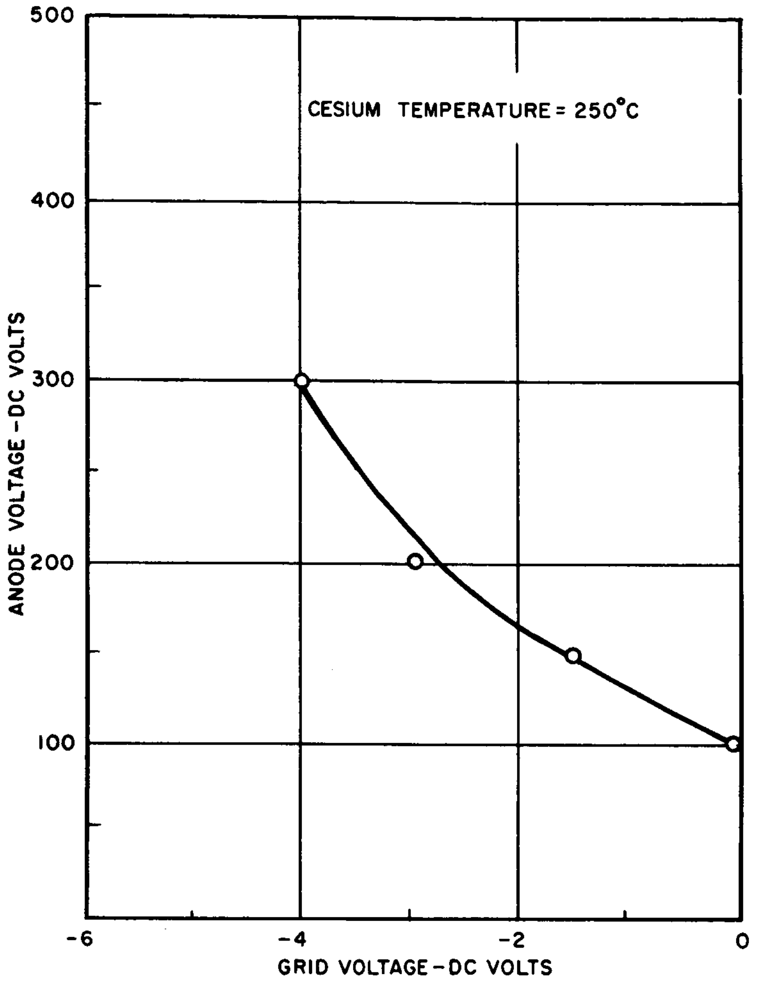

Figure 54 - Grid Characteristic, Type Z-7009, Tube No. 22

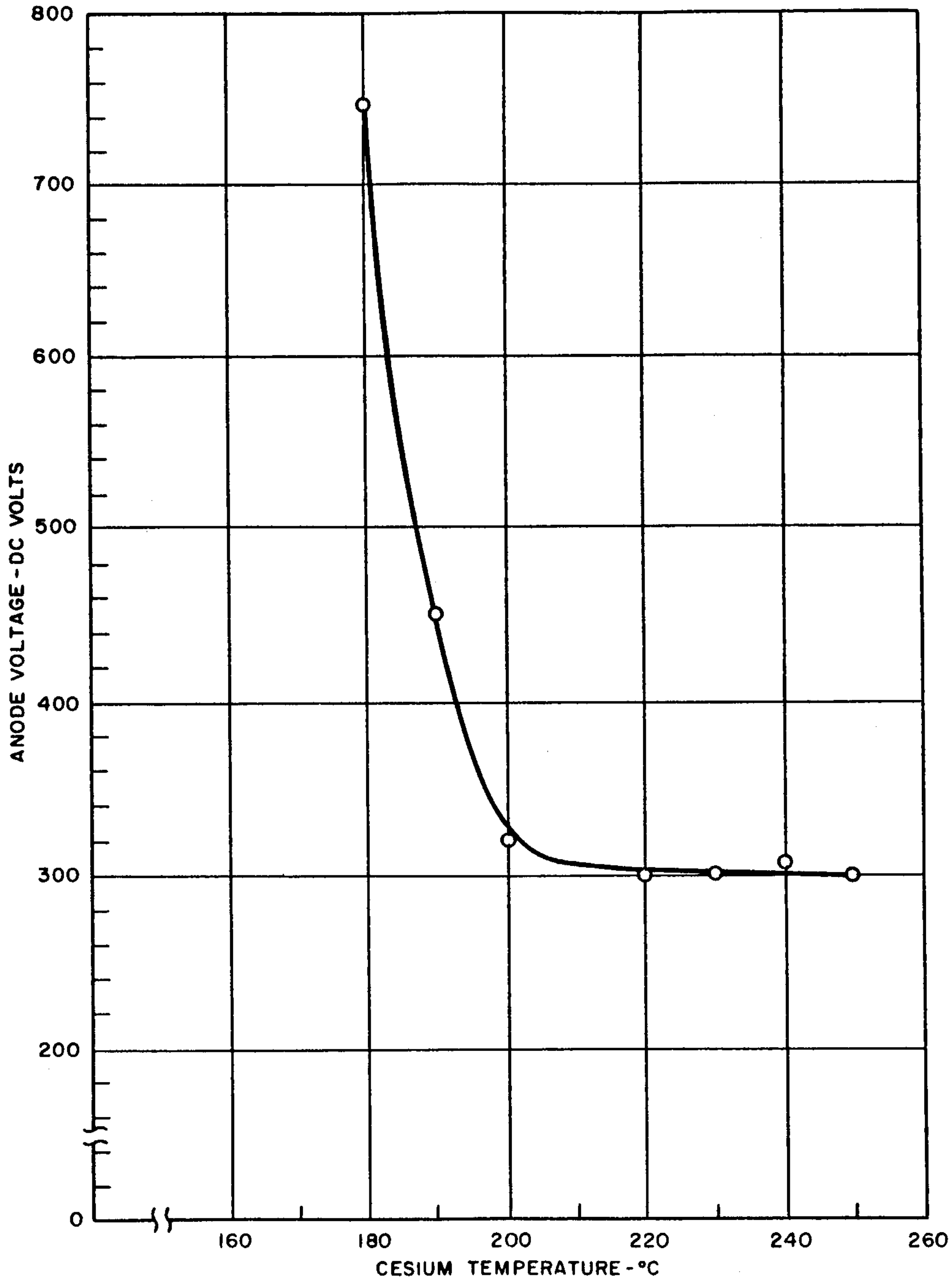

Figure 55 - Maximum Controllable D-C Voltage Versus Cesium Temperature, Type Z-7009, Tube No. 22

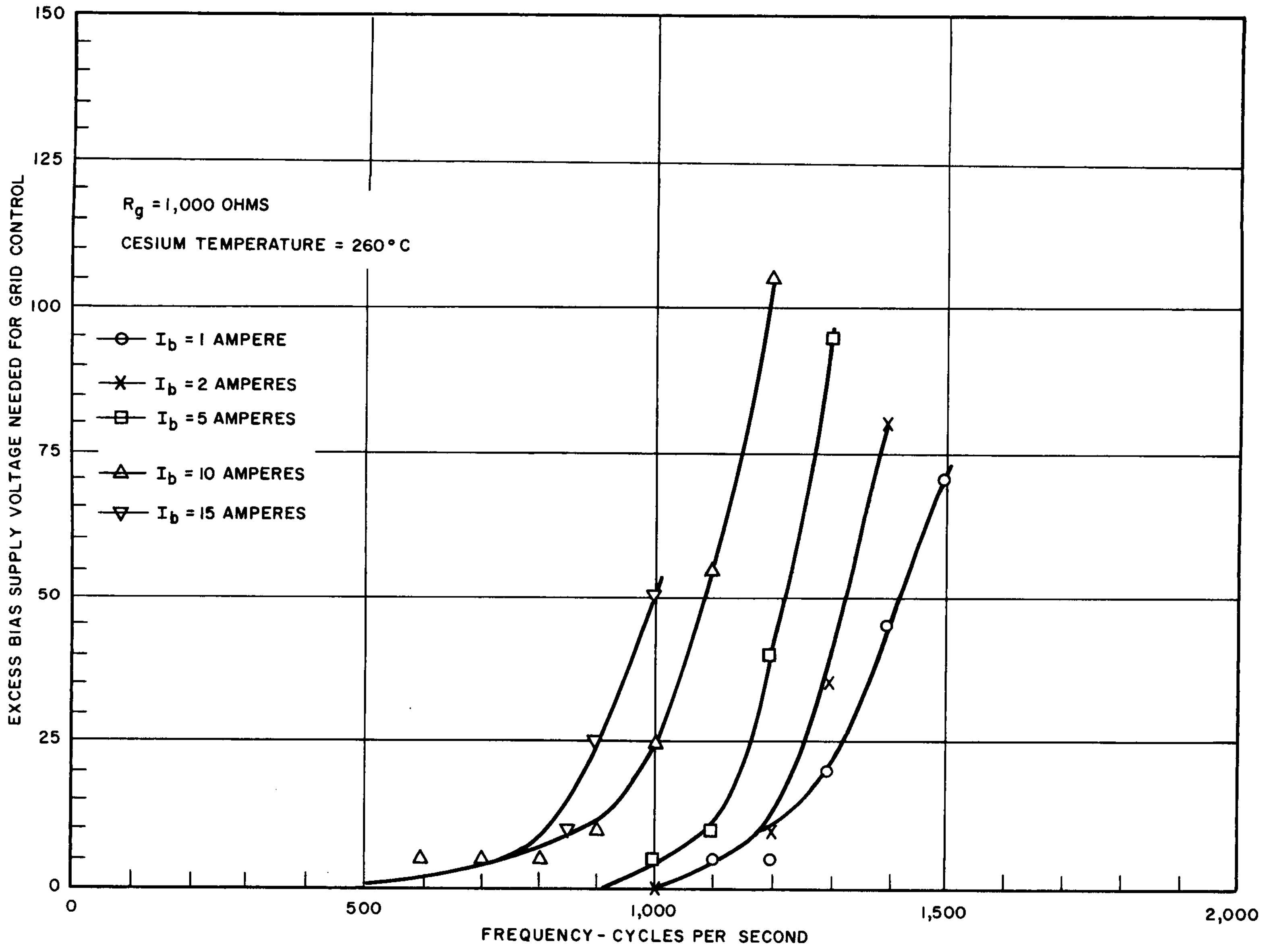

Figure 56 - High-Frequency Performance, Type Z-7009, Tube No. 22

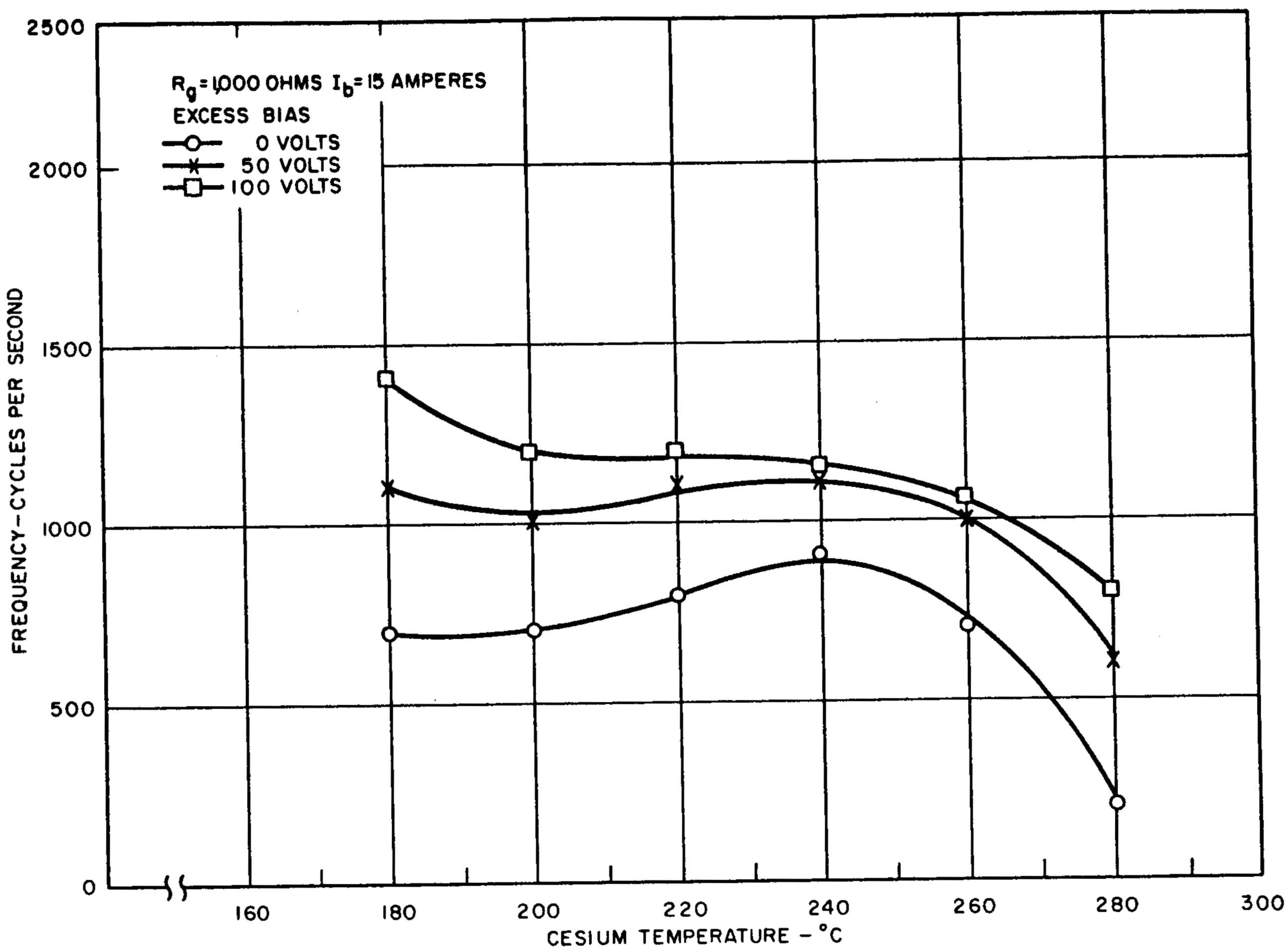

Figure 57 - Maximum Frequency Versus Cesium Temperature
Type Z-7009, Tube No. 22

In the interest of economy, a simulation circuit was planned which would permit the Z-7009 to be connected to the 110-volt A-C shop line for one half-cycle and to a low-current high-voltage transformer on the subsequent half-cycle. Thus, the tube could conduct 15 amperes average from the low-voltage shop line on even half-cycles and be subjected to the low-power high-voltage circuit on odd half-cycles. With variac control, the inverse voltage applied to the tube could be varied between 0 and 750 volts. The necessary switching functions would be accomplished by two industrial thyratrons as shown in Figure 58.

In the interest of time, the endurance run was initiated before the simulation circuit was available. Thus, approximately 500 hours of operation were logged with a 110-volt A-C supply only, wherein the inverse voltage was limited to 150 volts. From 500 hours on, the tube was subjected to higher inverse voltages.

The tube selected for the endurance run was Type Z-7009, No. 22, with a thick copper grid. As mentioned previously, this tube performed initially with a grid temperature as high as 350°C. Subsequent experience, however, disclosed the fact that freedom from grid emission could not be assured unless the heat sink temperature for the grid was limited to 300°C. The cause of the apparent reduction in the grid emission ceiling of 50 degrees is not fully understood, but the following factors have a bearing on the matter.

1. Early testing was conducted at a reservoir temperature of approximately 250°C. It was subsequently determined that grid emission reached a maximum when the reservoir temperature was reduced to 220 to 230°C. Maximum permissible grid temperature as a function of reservoir temperature is shown in Figure 59.

2. A slight change in the work function of cesium on the copper (grid) substrate may have occurred.

3. The early test possibly was not conducted over a period of sufficient duration to allow all of the surroundings -- such as tube support stand and bell jar -- to reach equilibrium temperature.

Throughout the endurance run, anode temperature was maintained at 300°C or higher, and the grid was held at 290 to 300°C. Periodic tests were taken to reveal the status of the following tube parameters: tube drop at 100 amperes peak, tube drop at 15 amperes average (with D-C supply),

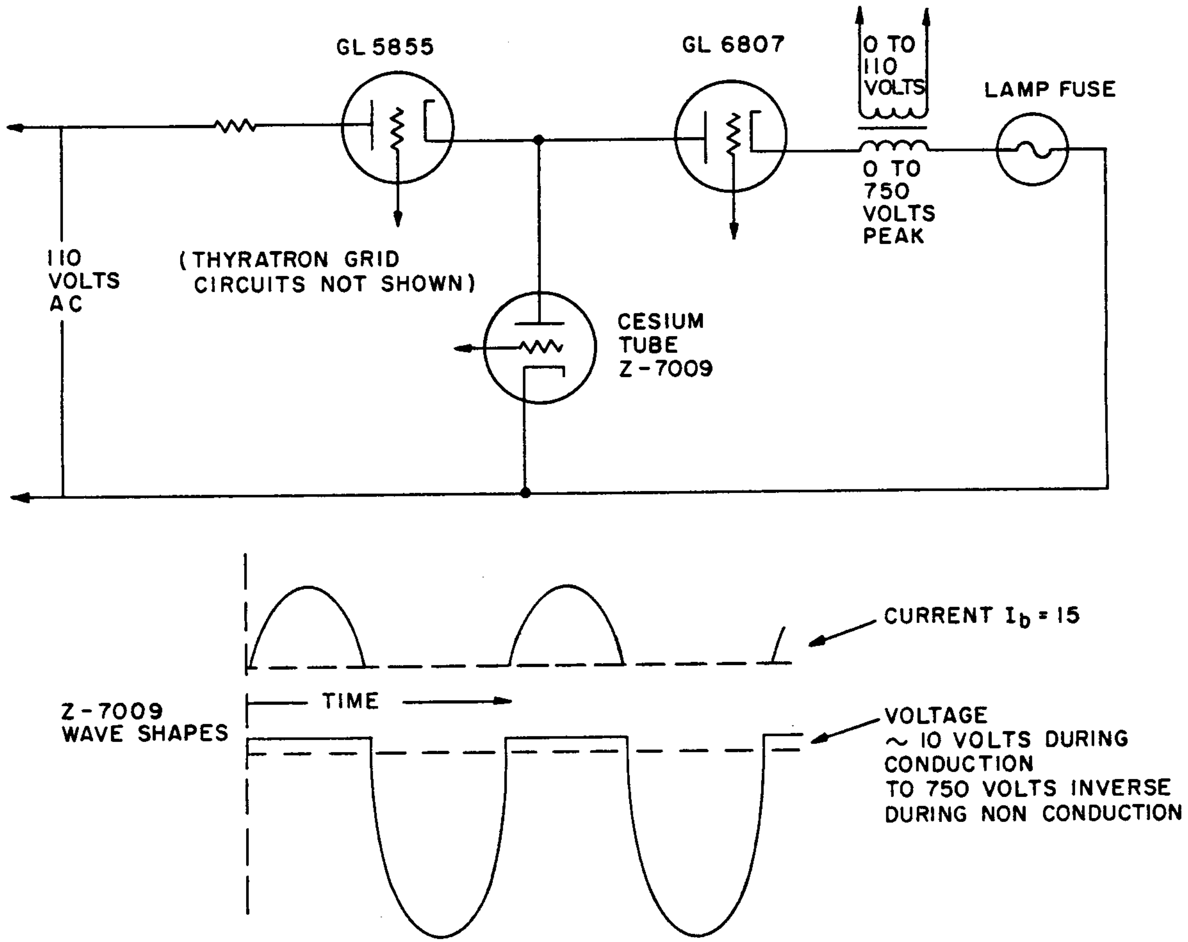

Figure 58 - Schematic of High Inverse Simulation Circuit